METHOD AND APPARATUS FOR MIXING FLUIDS

Priority Statement

This application is a continuation-in-part of U.S. Patent Application No. __/___,___, filed September 12, 2003, which is a conversion of U.S. Provisional Application No. 60/418,989, filed October 15, 2002, this application claims the benefit of the earlier filed applications under 35 U.S.C. § 119(e) and 35 U.S.C. §120 which are also incorporated by reference herein.

Background of the Invention

Field of the Invention

The invention relates in general to apparatus and methods for controlling the delivery of a fluid, and to mixing of two or more fluids, and in particular, to methods and apparatus wherein the mixing of two or more fluids create and/or control physical and/or chemical changes in those fluids.

Description of the Related Art

Many physical and chemical processes require the delivery of a first fluid, and of mixing of two or more fluids together. The effectiveness of the mixing in such processes is dependent upon many physical phenomena. Mixing may depend upon the surface area of a liquid or the interfacial area between the fluids (e.g., a liquid, a vapor, and/or a gas) that are to be mixed. For heat exchange between two fluids in direct contact, the process depends in part on the interfacial area between the two fluids and thus on the specific interfacial area (surface area per mass). In another example, chemical reactions between a liquid and a gaseous fluid typically occur between the vapor evaporated from the liquid, and the surrounding gaseous fluid.

Traditional methods for mixing two fluids together rely on relatively few injection nozzles, which are arranged to inject a first fluid into a second fluid. Such methods produce areas where local concentrations may be higher or lower than the desired average concentration. Such discontinuities may adversely effect the desired physical or chemical processes. There is a

general need for an apparatus and method for improving the mixing of two or more fluids together.

Summary of the Invention

Accordingly, one exemplary embodiment of the invention involves an apparatus for mixing a first fluid with a second fluid. The apparatus comprises a fluid distribution portion comprising at least one tubular portion having an outer surface and an inner surface, the inner surface defining a first flow path for the first fluid, a duct that defines a second flow path for the second fluid, the duct having an axial direction and a first and second transverse directions mutually distinct from the axial direction, the first and second transverse directions defining a plane through an axial location and containing a cross-sectional area of the duct, a first fluid delivery system for supplying the first fluid to the fluid distribution portion a second fluid delivery system for supplying the second fluid to the duct; the tubular portion comprising a plurality of orifices each forming a third flow path along which the first fluid can be injected into the second fluid within the duct; and wherein the outer surface of the tubular portion comprising the orifices is positioned within the duct in the second flow path and the orifices when projected onto a plane containing the first and second transverse directions have an average spatial density of at least about 10,000 orifices per square meter of duct cross sectional area.

Another exemplary embodiment of the invention involves a method of mixing a first fluid with a second fluid. The method comprises providing a fluid distribution portion comprising at least one tubular portion having an outer surface and an inner surface, the inner surface defining a first flow path for the first fluid, providing a duct that defines a second flow path for the second fluid, the duct having an axial direction and a first transverse direction and a second transverse directions perpendicular to the axial direction, the first and second transverse directions at an axial location defining a plane comprising a cross-sectional area of the duct, positioning the at least one tubular portion in the duct such that it extends in a direction having a component in the first transverse direction; providing a plurality of orifices on the at least one tubular portion, each orifice forming a third flow path along which the first fluid can be delivered into the second fluid

within the duct; providing a first fluid delivery system for providing the first fluid to the first flow path; controlling a delivery pressure of the first fluid; configuring at least one of the (i) the size of the plurality of orifices in the transverse direction, (ii) the linear density of the plurality of orifices in the transverse direction or (iii) the delivery pressure of the first fluid to deliver a non-uniform amount, with respect to the first transverse direction, of the first fluid into the second fluid to achieve a desired distribution of the first fluid in the second fluid in the first transverse direction downstream of the fluid distribution portion.

Another exemplary embodiment of the invention relates to method of mixing and exchanging heat between a first fluid and a second fluid. The method comprises providing a delivery member for a first fluid, the delivery member comprising tubular portions with a plurality of orifices; providing a duct for a second fluid through, the duct having a duct axis and encompassing the orifices; configuring a non-uniform transverse distribution of orifice sizes along at least one of a first direction transverse to the duct axis, and controlling the differential ejection pressure between the first fluid within the orifices and the second fluid outside the orifices along at least a first direction transverse to the duct axis; providing a non-uniform density in the transverse direction of the orifices on the delivery member, delivering the second fluid through the duct; and and delivering the first fluid through the delivery member to control the temperature of the second fluid exiting the duct.

Another exemplary embodiment relates to a method of radiatively exchanging heat with a first fluid. The method comprising providing tubular portions comprising numerous orifices within a duct; configuring the orifices to have a non-uniform spatial distribution with respect to a transverse axis of the duct; configuring the orifices to have a non-uniform size distribution with respect to the transverse axis of the duct; delivering a first fluid to the tubular portions with a non-uniform differential ejection pressure with respect to the transverse axis; controlling the temperature of the first fluid delivered to the tubular portions, controlling the temperature of a wall of the duct, and controlling the radiation flux from the duct wall to the first fluid being delivered from the tubular portions to the duct.

Another exemplary embodiment relates to a method of mixing a first fluid with a second fluid. The method comprises providing a fluid distribution portion comprising at least one tubular portion having an outer surface and an inner surface, the inner surface defining a first flow path for the first fluid, providing a duct that defines a second flow path for the second fluid, the duct having an axial direction and a first transverse direction and a second transverse directions perpendicular to the axial direction, the first and second transverse directions at an axial location defining a plane comprising a cross-sectional area of the duct, positioning the at least one tubular portion in the duct such that it extends in a direction having a component in the first transverse direction; and dynamically controlling the distribution of the first fluid into the second fluid with respect to the first transverse direction downstream of the fluid distribution portion by controlling the pressures at both ends of the fluid distribution portion.

For purposes of summarizing the invention, certain aspects, advantages and novel features of the invention have been described herein above. Of course, it is to be understood that not necessarily all such advantages may be achieved in accordance with any particular embodiment of the invention. Thus, the invention may be embodied or carried out in a manner that achieves or increases one advantage or group of advantages as taught or suggested herein without necessarily achieving other advantages as may be taught or suggested herein.

All of these embodiments are intended to be within the scope of the invention herein disclosed. These and other embodiments of the invention will become readily apparent to those skilled in the art from the following detailed description of the preferred embodiments having reference to the attached figures, the invention not being limited to any particular preferred embodiment(s) disclosed.

Brief Description of the Drawings

Having thus summarized the general nature of the invention and some of its features and advantages, certain preferred embodiments and modifications thereof will become apparent to those skilled in the art from the detailed description herein having reference to the figures that follow, of which:

FIG. 1 is a schematic-perspective view of an exemplary embodiment of a general distributed direct contact array system comprising a distribution member with a plurality of orifices and a controller;

FIG. 2 is a cross-sectional section view of another embodiment of a distribution member comprising multiple orifices;

FIG. 3 is a cross-sectional view of another embodiment of a thinned distribution member;

FIG. 4 is a cross-sectional view of another embodiment of a curvaciously thinned distribution member;

FIG. 5 is a cross-sectional view of another embodiment of a thinned distribution member comprising inward;

FIG. 6 is a cross-sectional view of another embodiment of a curvaciously thinned distribution member comprising outward orifices;

FIG. 7 is a perspective view of two linear offset arrays of uniform orifices on a distribution member;

FIG. 8 is a perspective view of columnar arcs of uniform orifices on both sides of a distribution tube;

FIG. 9 is a perspective view two offset lines of orifices increasing and then decreasing in orifice size along and on both sides of a distribution member;

FIG. 10 is a perspective view of a distribution member containing orifices positioned and sized in a pseudo-random fashion with varying net orifice area spatial density;

FIG. 11 is a perspective view of a distribution member containing orifices with spacing decreasing and then increasing thus transversely varying the net orifice area spatial density;

FIG. 12 is a perspective view of a hemispherical end to a distribution member with orifices;

FIG. 13 is a schematic cross-sectional view of the wall of the elongated distribution member of the distributed fluid contactor of FIG. 101A;

FIG. 14 is a elevation view of an embodiment for hexagonally arranging the orifices on the distribution member of FIG. 101A;

FIG. 15 is an elevation view of another embodiment for rectangularly arranging the orifices on the distribution member;

`FIG. 16 is a perspective of a radial variation in orifice spatial density in a circular array of distribution members;

FIG. 17 is a perspective view of a transverse variation in orifice spatial density in a rectangular array of perforated tube connected to manifolds, having features and advantages in accordance with one embodiment of the invention;

FIG. 18 is a conceptual diagramatic view of radial orifice spacing as a function of fluid flows, tube gap and jet penetration in an exemplary embodiment;

FIG. 19 is a conceptual diagramatic view of maximum radial orifice size configuration designed to achieve a desired evaporation distance as a function of fluid velocity and evaporation time in an exemplary embodiment;

FIG. 20 is a schematic view of the transverse orifice diameter and spacing, first fluid pressure and resultant first fluid flow per orifice, across an annulus;

FIG. 21 is a conceptual view of varying orifice size to provide different jet penetrations in an exemplary embodiment;

FIG. 22 is a schematic perspective of tube connection to a manifold.

FIG. 23 is an conceptual view of varying orifice circumferential orientation to provide different micro-jet gap penetrations in an exemplary embodiment;

FIG. 24 is an conceptual view of varying orifice circumferential orientation to provide concentrated asymmetric micro-jet gap penetrations in an exemplary embodiment;

FIG. 25 is an conceptual view of varying orifice circumferential orientation to provide distributed asymmetric micro-jet gap penetrations in an exemplary embodiment;

FIG. 26 is a schematic view looking downstream of an exemplary embodiment of alternating micro-jets penetrating the gap between two distribution members;

FIG. 27 is a schematic view, transverse to the flow, of an exemplary embodiment of alternating micro-jets penetrating the gap between two distribution members;

FIG. 28 is a schematic view looking downstream of an exemplary embodiment of opposed micro-jets penetrating the gap between two distribution members;

FIG. 29 is a schematic view, transverse to the flow, of an exemplary embodiment of opposed micro-jets penetrating the gap between two distribution members;

FIG. 30 is a schematic view of aligned distribution members with diagonally opposed offset orifices;

FIG. 31 is a schematic view of alternating parallel distribution members with diagonally opposed orifices;

FIG. 32 is a schematic view of aligned distribution members with chevron orifices;

FIG. 33 is a schematic view of alternating distribution members with chevron orifices;

FIG. 34 is a cross-sectional view of a circular distribution member;

FIG. 35 is a cross-sectional view of an oval distribution member;

FIG. 36 is a cross-sectional view of a streamlined distribution member;

FIG. 37 is a cross-sectional view of a flattened distribution member;

FIG. 38 is a cross-sectional view of a flattened dual chamber distribution member;

FIG. 39 is a cross-sectional view of a flattened single chamber distribution member;

FIG. 40 is a cross-sectional view of an asymmetric streamlined distribution member;

FIG. 41 is a cross-sectional view of a "bluff" or triangular distribution member;

FIG. 42 is a schematic cross section view of a downstream cusped bluff distribution member in an exemplary embodiment;

FIG. 43 is a perspective view of an exemplary embodiment of a compound distribution member;

FIG. 44 is a perspective view of another embodiment of a compound distribution member, which has an aerodynamic shape;

FIG. 45 is a perspective view of another embodiment of a compound distribution member, which has a ribbed tubular structure to support perforated foils;

FIG. 46 is a schematic cross-sectional view of an exemplary embodiment of a streamlined distribution member formed by bonding two strips along two dissimilar wires;

FIG. 47 is a schematic cross-sectional view of an exemplary embodiment of a streamlined distribution member formed by wrapping a thin strip about tube stiffeners;

FIG. 48 is a schematic cross-sectional view of an exemplary embodiment of a streamlined distribution member formed by wrapping a thin strip about two similar wires;

FIG. 49 is a schematic cross-sectional view of an exemplary embodiment of a streamlined distribution member formed by abutting and bonding two thinned strips on either side of two dissimilar wires;

FIG. 50 is a perspective view of an exemplary embodiment of a distributed contactor having an elliptical circular array of distribution members positioned across the flow within a substantially circular duct;

FIG. 51 is an expanded view of a portion of the distributed contactor of FIG. 50;

FIG. 52 is a schematic perspective view of an exemplary embodiment of a distributed contactor having an array of distribution members oriented axially substantially parallel to the flow within an annular duct;

FIG. 53 is a schematic perspective view of a tent shaped array of distribution members orientated at an angle to the flow within a rectangular duct;

FIG. 54 is a front view of a circular array of distribution members;

FIG. 55 is a front view of a rectangular array of distribution members;

FIG. 56 is a front view of an annular array of distribution members;

FIG. 57 is a perspective view of a three dimensional downstream concave array of distribution members;

FIG. 58 is a perspective view of a three dimensional rectangular tent array of distribution members;

FIG. 59 is a perspective view of a three dimensional annular tent array of distribution members;

FIG. 60 is a schematic view of an exemplary embodiment of an annular array of radial distribution members connected to multiple sub-manifolds formed in arcs, forming a spoke type annular array;

FIG. 61 a schematic view of a fluid mixing control system.

FIG. 62 is a schematic view of an exemplary embodiment of an annular axially multi-array configuration of circumferential distribution members connected to multiple sub-manifolds formed in radial spokes;

FIG. 63 is an enlarged upstream cross sectional view of overlapping inter tube sprays;

FIG. 64 enlarged view of three axially spaced tubes with differing orifice specific number spatial density;

FIG. 65 is a perspective view of a three dimensional cylindrical array of distribution members;

FIG. 66 is a perspective view of a three dimensional "top hat" array of distribution members;

FIG. 67 is a perspective view of a bulbuous array of distribution members;

FIG. 68 is a perspective view of an exemplary embodiment of streamlined stiffeners supporting an exemplary embodiment of "funnel" conical array of distribution members;

FIG. 69 is a perspective view of an exemplary embodiment of downstream increasing helical "horn array";

FIG. 70 is a schematic view of distribution members configured in a "tent" or "conical" arrangement oriented in a "funnel" shape within a duct;

FIG. 71 is a schematic view of distribution members oriented about "pleated" array, within a duct;

FIG. 72 is a schematic view of distribution members arranged in a "compound" array;

FIG. 73 is a schematic illustration of an exemplary embodiment for controlling fluid flow by minimum largest) orifice differential fluid pressure switch;

FIG. 74 is a schematic illustration of an exemplary embodiment of flow control relative to all orifice differential fluid pressure;

FIG. 75 is a schematic illustration of an exemplary embodiment of flow control by graded differential fluid pressure;

FIG. 76 is a schematic illustration of an exemplary embodiment of flow control by digital pulsation of fluid pressure;

FIG. 77 is a schematic illustration of an exemplary embodiment of flow control by frequency modulation of fluid pressure;

FIG. 78 is a schematic illustration of an exemplary embodiment of flow control by amplitude modulation of fluid pressure;

FIG. 79 is a schematic view of an upstream distribution member in a grounded "horn" conical array with a downstream grid connected to a high voltage power supply;

FIG. 80 is a schematic view of an exemplary embodiment of two sets of distribution members alternatingly connected to negative high voltage electrode or to ground, within a duct;

FIG. 81 is a schematic view of an exemplary embodiment of distribution members connected to a negative high voltage, within a grounded duct;

FIG. 82 is a schematic illustration of an exemplary embodiment of a multiple duct horizontal distributed contactor

FIG. 83 is a schematic view of a direct contact heat exchanger;

FIG. 84 is a schematic view of a power conversion system comprising an exemplary embodiment of a direct fluid contactor configured to deliver a vaporizable first fluid into a second fluid;

FIG. 85 is a schematic cross section of a peripheral distribution member in a duct with multiple orifice sizes and jet penetrations in an exemplary embodiment;

FIG. 86 is a schematic cross section of an axial distribution member in a duct with multiple orifice sizes and jet penetrations in an exemplary embodiment;

FIG. 87 is a schematic section of a particle separator utilizing a direct contact heat exchanger..

FIG. 88 is a perspective view of distribution members encircling a cylindrical duct and connected to manifolds;

FIG. 89 is a perspective view of distribution members oriented about a cylindrical duct and parallel to its axis;

FIG. 90 is a perspective view of distribution members encircling a cylindrical port with a valve;

FIG. 91 is a schematic perspective of a radiative heat transfer system to cool distributed drops;

FIG. 92 enlarged perspective view of a contactor tube;

FIG. 93 is a schematic perspective of a radiative heat transfer system to heat distributed drops; and

FIG. 94 Distributed Contactor Modeling Method.

Detailed Description of the Preferred Embodiment

A list of some components and certain nomenclature utilized in describing and explaining the preferred embodiments of the invention follow:

2 **Distributed Contactor System**
3 First Flow Path
4 Second Flow Path
5 Third Flow Path
6 Tube Inner Surface
7 Tube Outer Surface
8 Tube
9 Tube axis

10 **Distributed Contactor Perforated Tube** or Distribution Member
11 First Fluid Distributed Contactor Perforated Tube or Fuel Contactor
12 Liquid Fuel Distributed Contactor Perforated Tube or Diesel Contactor
13 Gaseous Fuel Distributed Contactor Perforated Tube
14 Thermal Diluent Fluid Distributed Contactor Perforated Tube
15 Fuel fluid Passage
16 Dual Passage Contactor Perforated Tube
17 Thermal Diluent Passage
18 Compound Dual Passage Contactor Perforated Tube
19 Bridging Fuel fluid Contactor Perforated Tube
20 Concentric Passage Contactor Perforated Tube
21 Curvilinear Perforated Tube Section or Arc
22 Insulated Diluent Contactor Perforated Tube
24 Insulated Diluent Spray Contactor Perforated Tube
26 Streamlined Triple Passage Contactor Perforated Tube

28 Cusped Triple Passage Contactor Perforated Tube

30 Tube Wall
31 Intra-tube wall
32 Thin Tube Wall Section
33 Tube Side Wall
34 Thermal Barrier Coating
35 Mechanically Protective Coating, Abrasion or Erosion Barrier Coating
36 Internal Tube Stiffener or Tube Structural Section
37 External Tube Support
38 Tube Structural Rib
39 Bond
40 Fin-stiffener, or Thermal Fin
42 Web-stiffener
44 Perforated Web
46 Fin-stiffener Tube
48 Dual Fin-stiffener Tube

50 Tube Vibrator
54 Curvilinear flexible supply tube

56 Combustor
57 Inner combustor mount
58 Outer combustor mount
59 Combustor wall

60 Combustor liner
61 Tube-fin liner
62 Tube-fin coolant passage
64 Plane fin
66 Fluted fin
67 Fin expansion Gap
68 Thermal Barrier Coating
69 Compound wrapped liner
70 Tube-fin Stiffening Rib
72 Flexible array structural support
74 Tube connecting hole

80 Orifice (may comprise non-circular openings)
82 Fuel Fluid Orifice or Fuel Orifice
83 Thermal Diluent Orifice or Diluent Orifice
84 Axial Orifice Orifice with predominantly axial component

85 Radial Orifice Orifice with predominantly radial component
86 Angled Orifice Orifice with angle significantly off perpendicular to flow
87 Larger Orifice Opening
88 Orifice Entrance
89 Smaller Orifice Opening
90 Orifice Exit
91 Hexagonal Orifice Array
92 Cartesian or Rectangular Orifice Array
93 Columnar Array
94 Fluid Sampler Tube
96 Sampler-Diluent Contactor Tube

100 Flame Holder, Ignition Authority, Pilot Light, or Pilot Flame
102 Modified Toroidal Chamber
103 Internally Concave Redirector
104 Fuel fluid Tube/Passage
106 Thermal Diluent Tube/Passage , Diluent Tube Passage, Duct or Member
107 Oxidant Intake Port
108 Main Oxidant Tube/Passage
110 Pilot Oxidant Tube/Passage
111 Circumferential Passage
112 Mixture Delivery Port
114 Hot Gas Intake Port
116 Hot Gas Delivery Flame Tube
118 Flame Holder Structural Support
120 Insulation/Thermal Barrier Coating
122 Streamlined Shroud
124 Igniter
126 Igniter Excitation Source

130 Fluid Duct
131 Fluid Sub-Duct, Smaller Fluid Duct
132 Fluid Duct Wall
133 Fluid Duct Axis
134 Fluid Duct Entrance Combustor Inlet, Evaporator Inlet, Saturator Inlet
136 Fluid Duct/Combustor Exit Combustor Outlet, Evaporator Outlet, Saturator Outlet
137 Fluid Duct Hub
138 Duct Wall Cooling Channel
139 Fluid duct "window", electromagnetically transparent wall.
140 Focusing Resonant Duct
142 Spring-Fin Coolant Duct

144 Circular Duct Elliptical Duct, Cylindrical Duct
145 Rectangular Duct
146 Annular Duct
148 Diluent Fluid Duct

150 Insulation
152 Insulation Wedge
154 Insulation Ring
156 Insulation Tile
158 Radial Insulation Spring
160 Axial Insulation Spring

168 Combustor External Enclosure

170 Pressure vessel
172 Pressure Vessel Wall
174 Pressure Vessel End Cap/Port
176 Pressure Vessel Feed-Through
178 Pressure Vessel Cooling System

180 Progressive Thermal Shield
182 Progressive Perforated Thermal Shield
184 Progressive Insulation Thermal Shield
186 Progressive Radiation Shields

190 Engine Cylinder
192 Combustion Cylinder
194 Duct Slide Port, Cylinder Slot Port
196 Duct Side Port, Cylinder Side Port
197 Reciprocating Piston
198 Cylinder Wear Bar

200 Compound Perforated Tube , Compound Distribution Tube
202 Structural Tube Support

220 Multi-passage compound contactor tube
222 Tube Passage or Tube Duct
224 First Fluid Tube Duct e.g. Fuel Fluid Tube Passage
226 Inter-passage Tube Wall
228 Third Fluid Tube Duct e.g. Thermal Diluent Tube Passage, Diluent Tube Passage

230 Flow control valve
231 Sub-duct Valve
232 Purge Valve
233 Sub-manifold Valve

240 Manifold
242 Fuel fluid Manifold
244 Thermal Diluent Manifold , Diluent Manifold
246 Multi-passage Manifold
247 Central Manifold Header
248 Hydraulic Feed-through
249 Manifold Wall
250 Manifold Connecting Hole
252 Manifold End Opening
254 Secondary Manifold or Sub-Manifold
255 Tube-Duct Junction
256 Mounting Indent/Ridge
257 Inter-tube duct
258 Bond layer
259 Compound Secondary Manifold

260 Direct Contactor Perforated Tube Array
261 Downstream Increasing Concave Tube Array
262 "Horn" Conical Tube Array
263 Downstream Decreasing Convex Tube Array
264 "Funnel" Conical Tube Array
265 Elliptical Planar Tube Array, or Pseudo-Elliptical Array, e.g. Circular Planar Tube Array
266 Rectangular Planar Tube Array or Trapezoidal Planar Array
267 Annular Planar Tube Array or Annular Planar Tube Section
268 Rectangular Tent Tube Array or Pyramidal Tube Array
269 Annular Tent Tube Array Annular Tent Tube Section
270 Elliptical Tube Array e.g. Cylindrical Tube Array
271 Can Tube Array or "Top Hat" Tube Array
272 Cusped Tube Array
273 Bulbuous Tube Array or "Dandelion" Tube Array
274 Perforated Contactor Tube Array Module Contactor Tube Array Section
275 Modular Combustor or Can Combustor

276 Heater Tube
277 Interior Heater Tube Wall
278 Exterior Heater Tube Wall

279 Wall of Heater Tubes or Heater Tube Bank

280 Structural support
282 Array Mount
284 Pleated Array

290 Micro-swirler
291 Over tube "Striding" "saddle" airfoil micro-swirler
292 "Sitting" saddle airfoil micro-swirler
293 Between Tube "Striding" "T-shirt" vane micro-swirler
294 "Sitting" T-shirt micro-swirler
295 Helical micro-swirler vane
296 Micro-swirler rib
297 Micro-swirler airfoil
298 Micro-swirler vane
299 Mini-swirler

300 High Voltage Power Supply
301 Power Supply
302 Ground electrode
304 Positive Electrode
306 Negative Electrode
308 First voltage electrode
310 Second voltage electrode
312 Third voltage electrode
314 Support Insulator
316 High Voltage Feed-through

320 Combustor Electrode , distributor electrode
322 Fuel fluid Array Electrode
324 Diluent Array Electrode
326 Grid Electrode
328 Cooled Tubular Electrode
330 Axial Electrode
332 Peripheral Electrode
334 Mid-duct Electrode
340 Conductive-Liquid Isolator
342 Grounded supply pump
343 Perforated liquid distributor
344 Isolated liquid drop tower
346 Droplet collector
348 Insulating supports

350 Elevated voltage supply pump

356 First Fluid Supply
358 Third Fluid Supply
360 First Fluid Delivery System or Fuel Delivery System
361 Third Fluid Delivery System or Diluent Delivery System
362 Storage Tank
364 Supply Pump, Fluid Pump
366 Delivery Pump
367 Differential Manifold Pump
368 Recirculating Pump
369 Fluid Fluctuation Damper
370 Pressure/Flow Modulator
372 Pilot Flame/Flame Holder Fuel Delivery System
373 Pilot Flame/Flame Holder Thermal Diluent Delivery System
374 Rotary Actuator
376 Rotary Pump Head
378 Linear Actuator
379 Solenoid

380 Filter
382 Coarse Fluid Filter, Coarse Liquid Filter, or Coarse Fuel Filter
384 Fine Fluid Filter, Fine Liquid Filter, or Fine Fuel Filter
386 Uniform Orifice Filter or Maximum Size Filter
388 Recirculating Bypass Filter
390 Fluid Filter , Gas Filter or Air Filter
392 Spray Direct Contact Filter
394 Flow homogenizer/straightener
398 Second Fluid Supply
400 Second Fluid Delivery System also termed Oxidant Delivery System
402 Distributed Contactor Fogger
404 Distributed Contactor Precooler
406 Blower
407 Compressor
408 First / Low Pressure Compressor
409 Blower/Compressor intake/entrance
410 First Intercooler
412 Second / Intermediate Pressure Compressor
414 Second Intercooler
416 Third / High Pressure Compressor
417 After cooler
418 Pilot/Flame Holder Oxidant Delivery System

420 **Diffuser**
421 Diffuser Vanes or Splitter Vanes
422 *Connecting Duct*
424 Combustor
426 Transition Zone/Piece

440 **Expander** (Turbine or engine)
442 High Pressure Turbine
444 Low Pressure Turbine
446 Turbine Stage
448 Turbine Vane ("Nozzle")
450 Turbine Blade ("Bucket")

460 **Drive System**
462 First Drive Shaft
464 Second Drive Shaft
466 Gear Train
468 Variable speed drive

470 **Heat Exchanger or Heat Recovery System**
472 *Superheater*
474 *Evaporator ("Boiler")*
476 *Economizer*
478 *Preheater*
480 Condensor
481 Collector Duct
482 Surface (Flue Gas) Condensor
483 Direct Contact Heat Exchanger or Direct Fluid Contactor
484 Direct Contact Condensor

486 ***Cooling System***
488 *Liquid - Liquid Heat Exchanger*
490 *Air-Liquid Heat Exchanger*
492 *Recirculation Pump*
494 *Supply Water Tank*
496 *Deionized Water Tank*
498 **Spray Cleaning System**
500 **Generator**
502 **Recompressor**

510 Stack, chimney, natural draft device or flare

512 *Dry cooling tower*
514 *Wet cooling tower*
516 *Hybrid cooling tower*
518 *Exhaust Diffuser*

520 **Particulate separator or droplet separator**
522 Gravity Separator
524 Multi-duct Gravity Separator
526 Cyclone separator
528 *Electrostatic Precipitator*
530 Impingement Separator

540 ***Liquid Conditioner***
542 *Particulate Filter*
544 *pH Conditioner*
546 *CO_2 Stripper*
548 *Deionizer*

550 **Physical Parameter Sensors** or Transducers
552 Pressure Sensor or Transducer
554 Differential Pressure Sensor or Transducer
558 Temperature Sensor or Transducer
560 First Fluid Flow Sensor or Transducer e.g., Fuel Fluid Flow Sensor
562 Second Fluid Flow Sensor or Transducer e.g., Oxidant Fluid Flow Sensor
564 Third Fluid Flow Sensor or Transducer e.g., Thermal Diluent Fluid Flow Sensor

570 **Composition Sensor or Transducer**
572 Oxygen Sensor or Transducer
574 NOx Sensor or Transducer
576 Carbon Monoxide Sensor or Transducer (CO)
578 Unburned Hydrocarbon Sensor or Transducer (UHC)

580 **Motion Sensor/Speed Meter**
582 Pump Position Sensor or Transducer or Speed Meter, or Rotary Encoder
584 Compressor/Blower Position or Speed Meter or Transducer
586 Flow Modulator Control Sensor or Transducer (e.g., position / motion sensor)

588 Control System
590 **Controller**
592 First Fluid Controller e.g. Fuel Fluid Controller
594 Second Fluid Controller e.g. Oxidant Fluid Controller
596 Third Fluid Controller e.g. Thermal Diluent Fluid Controller

598 Heating Fluid Controller

900 Fluids
901 **First Fluid**, First Reactant Fluid, Fluid Fuel, or Thermal Diluent.
902 Drop or bubble of first fluid.
903 Jet or micro-jet of first fluid.
904 Second Fluid, Second Reactant, or Oxidant Fluid.
920 Energetic Fluid
924 Expanded Fluid
926 Flue Gas928 Cooled Fluid
930 Ambient Cooling Fluid
932 Ambient Cooling Water
934 Ambient Cooling Air
940 Condensate
942 Filtered Condensate
944 Deionized Condensate
950 Evaporated Diluent Fluid
952 Superheated Diluent Fluid

Tube Smallest Inner Diameter D_i
Tube Smallest Outer Diameter D_o
Tube Inner Area A_o
Tube Wall Thickness $T = (D_o - D_i)/2$
Thin Tube Wall Thickness t
Tube Center to Center Spacing H
Tube to Tube gap G
Orifice Inner Diameter d_i
Orifice Outer Diameter d_o
Orifice Area a_o
Orifice Inner Pressure at Inner Opening p_i
Orifice Outer Pressure at Outer Opening p_o
Orifice Center to Center Spacing h
Orifice to Orifice gap g
Orifice axial angle alpha (α)
Orifice transverse orientation angle theta (θ)
Orifice Array Width W

Profiles in the First Transverse Direction
Radial Pressure Distribution Ppr
Radial Velocity Distribution Vpr
Radial Temperature Distribution Tpr
Radial Density Distribution Rhopr

Radial Mass Flow Distribution Mdpr

Profiles in the Second or Circumferential Transverse Direction
Circumferential Pressure Distribution Ppc
Circumferential Velocity Distribution Vpc
Circumferential Temperature Distribution Tpc
Circumferential Density Distribution Rhopc
Circumferential Mass Flow Distribution Mdpc

The following detailed description of the preferred embodiments uses many technical terms. In an effort to improve clarity, several of these terms will be first described in this section. It should be appreciated that these technical terms are broad terms and are also used in their ordinary sense in addition to the definitions provided below.

First Fluid, commonly comprising one or more of a First Reactant Fluid, a Fluid Fuel, and a Thermal Diluent, herein also generically called a "Fuel Fluid". (e.g. a gaseous, liquid or fluidized powdered fuel or a mixture comprising fuel and thermal diluent typically passing through a Fuel Perforated Tube or Duct and moving out Orifices)

Second Fluid, commonly a Fluid comprising a second Reactant or an Oxidant, optionally comprising a thermal diluent fluid, herein also generically called an "**Oxidant Fluid**". (e.g. humid air or oxygen enriched air optionally mixed with steam, typically passing through a Fluid Duct across one or more perforated tubes, or else passing through an Oxidant Perforated Tube)

Third Fluid, commonly a "Thermal Diluent" or "Diluent Fluid" comprising an inert fluid or fluid with low reactivity such as a mild oxidant, capable of absorbing or giving off heat and changing enthalpy and temperature, herein also generically called a "**Thermal Diluent**" "**Diluent Fluid**" or "Cooling Diluent", sometimes distinguished as "Vapor Diluent" and "Liquid Diluent" when the diluent fluid is vaporizable. (e.g. water, steam, excess air, carbon dioxide, or recirculated products of combustion, typically passing through a Thermal Diluent Perforated Tube and out Orifices)

Energetic Fluid, a fluid capable of delivering energy, commonly a hot pressurized fluid comprising products of reaction and residual portions of the First Fluid and Second Fluid, and

commonly comprising Thermal Diluent (e.g. a hot pressurized fluid formed by combusting a fuel fluid with oxidant fluid such as compressed air and diluted with steam and excess air)

Expanded Fluid, fluid downstream of an expander or work engine such as a turbine or reciprocating engine, may also be termed Exhaust Fluid or Spent Fluid

Flue Gas, expanded energetic fluid exhausting through a flue

Cooled Fluid, a fluid with heat withdrawn such as downstream of a cooling heat exchanger or condensor

Distribution member, a member having a fluid passage through which fluid is delivered to orifices through which the fluid is distributed, such as a tube comprising orifices in a wall.

Orifice - a mouth or aperture of a tube, cavity etc.; opening

Opening - open place or part; hole; gap; aperture

Aperture - (1) an opening; hole; gap (2) the opening, or the diameter of the opening, in a camera, telescope, etc. through which light passes into the lens

Hole - an opening in or through a solid body, a fabric, etc.; a perforation; a rent; a fissure; a hollow place or cavity; an excavation; a pit; Webster 1913 rearranged

Duct - (1) a tube, channel, or canal through which a gas or liquid moves; . . . (4) a pipe or conduit through which wires or cables are run, air is circulated or exhausted etc.

Tube - a distributed member having an inner surface forming a passage defining a first flow path to deliver a first fluid, often having an elongated walled member.

Prescribed - herein generally refers to a parameter that is desired or needed, prescribed, predetermined, pre-selected or otherwise selected.

Curvilinear - the shape of a generic line comprising one or more linear and/or curvaceous sections as desired. E.g. comprising linear, polynomial and/or transcendent functions comprising conic sections, parabolic, elliptical, hyperbolic, sinusoidal, logarithmetic, exponential curves.

Coordinate system - system used to configure planar or spatial ducts or other fluid delivery system, comprising Cartesian, cylindrical, spherical, annular, or other suitable curvilinear co-ordinate systems or combinations thereof.

Differential Ejection Pressure - differential pressure across the orifice in the tube wall that ejects the first fluid as a jet.

All Orifice Differential Fluid Pressure Poda- the differential pressure across an array of orifices sufficient to eject fluid from all the orifices, including the smallest orifices 80.

Equivalence Ratio or Phi - the ratio of first reactant flow to second reactant flow or fuel fluid flow to oxidant fluid flow relative to the stoichiometric ratio of first reactant to second reactant or fuel fluid to oxidant fluid. I.e. the inverse of Lambda (E.g. diesel fuel to air ratio relative to stoichiometric diesel fuel to air ratio.)

Excess Oxidant Ratio, Lambda, or excess air ratio - the ratio of the second reactant or oxidant fluid flow to first reactant or fuel fluid flow relative to the stoichiometric ratio of second reactant to first reactant or stoichiometric oxidant fluid to fuel fluid. I.e. the inverse of Phi.

Lambda Distribution - the distribution of Lambda or relative stoichiometric ratio of oxidant fluid to fuel fluid (e.g. oxygen to fuel ratio relative to the stoichiometric ratio of oxygen to fuel.)

Rich mixture or composition - a fluid comprising more fuel (or less oxidant) than the stoichiometric ratio i.e. Lambda less than one or Phi greater than one.

Lean mixture or composition - a fluid comprising less fuel (or more oxidant) then the stoichiometric ratio. I.e. Lambda greater than one or Phi less than one.

Diluent enthalpy change - the change in enthalpy of a diluent between two states, including one or more of change due to heat capacity, latent heat of vaporization, and chemical dissociation.

Specific diluent enthalpy change - the change in enthalpy per unit mass between two states.

Total diluent enthalpy change - the diluent enthalpy change of all fluid components including excess oxidant fluid (in lean mixtures), excess fuel fluid (in rich mixtures), thermal diluent vapor, thermal diluent liquid and any other non ` constituents.

Excess heat generation - heat of combustion in excess of the heat required to increase combustion products to the desired energetic gas exit temperature.

Combustion cooling - the reduction in enthalpy of hot combustion gases equal to the excess heat generation and equal to the total increase in enthalpy of the total thermal diluent components.

Distribution - a function describing the variation of a parameter. Herein frequently used to describe the variation of the parameter along one or both transverse directions (e.g., radial and circumferential) or an axial direction. Also used for number distributions.

Profile - a function or distribution describing the variation of a parameter along a direction, such as in a radial direction in a cylindrical or annular duct. Herein may also be used for a ratio of two distributions, or to describe a "pattern" along a direction such as a circumferential direction. Sometimes used to emphasize spatial rather than number distributions.

Jet Discharge Cross Area - net cross-sectional area of the fluid jet as it exits the orifice.

Orifice Flow Factor - ratio of jet discharge cross-sectional area to total orifice discharge cross-sectional area

Fluid flow - the rate of flow of fluid on a mass basis, or the mol or volumetric rate if so stated.

Fluid flow distribution - the variation of the fluid flow along a direction, or along a curvilinear line as specified.

Fluid flow ratio - the variation in the ratio of two fluid flows, sometimes the distribution of this ratio.

Fluid flow ratio profile - the distribution of the ratio of two fluids along a transverse direction or along an axial direction or curvilinear line if so specified.

Fluid Flow Ratio Profile Range - the distribution of the range of upper and lower fluid flow ratios along a transverse direction or along an axial direction or curvilinear line if so specified.

Minimum Orifice Differential Pressure Podm - the differential ejection pressure across an array of orifices sufficient to eject fluid from the largest orifices 80.

Partial Orifice Differential Fluid Pressure Podp - the differential ejection pressure across an array of orifices sufficient to eject fluid from some of the larger orifices 80 but not from the smallest orifices.

Temperature - the thermodynamic temperature of a fluid at a point or the mean temperature of the fluid,

Temperature distribution - the variation of temperature in a fluid along a transverse direction or along an axial direction or curvilinear line as specified.

Temperature distribution range - the variation in upper and lower temperatures along a transverse direction or an axial direction or curvilinear line as specified.

Uncertainty - the uncertainty evaluated according to international definitions. Eg See NIST TN 1287.

Temperature uncertainty - the uncertainty in the temperature of the fluid or component.

Flow uncertainty - the uncertainty in fluid flow rate.

Ratio uncertainty - the uncertainty in ratio of fluid flow rates.

Turn Down - the ratio of minimum to maximum fluid flow rates, or described as reduction in flow divided by the maximum to minimum flow rates. E.g., 10% minimum to maximum flow ratio; 90% turn down; or a turn down of 10:1.

8.2Direct Contactor Perforated Tubes with Numerous Orifices Some preferred embodiments of the present invention relate to apparatus and methods for delivering a first fluid and for mixing two or more fluids and together. As will be described below, one embodiment utilizes a distribution member comprising a tube that is positioned within a duct forming a flow path. The tube comprises a large number of small orifices. The first fluid is injected through the orifices into the second flow path of a second fluid. By positioning the numerous small orifices across the flow path, very efficient mixing between the first and second fluids can be achieved.

Figure 1 illustrates one embodiment of a distributed contactor system 2, which can be used to mix a first fluid 901 with a second fluid 904. The first fluid is delivered to the intake of a manifold 240 by a first fluid delivery system 360. The second fluid is delivered to the inlet 134 of a fluid duct 130 by a second fluid delivery system 400. The fluid delivery is controlled by a

control system 580 which may include monitoring the pressure at the inlet and outlet of the duct 130. The distributed contactor system 2 includes a distributed perforated contactor 10 which is positioned within a fluid duct 130. External tube supports 37 are used to support the individual tubes 10. Flexible array supports 72 are used to support a distributed contactor array 260.

As shown in the cross section view Figure 2, the distributed fluid delivery member or contactor 10 that delivers the first fluid is formed in part from a fluid delivery duct such as from a tube, by forming numerous orifices 80 through a tube wall 30 of the tube. The tube wall 30 has an inner surface 6 that defines a first flow path 3 for a first fluid 901, and an outer surface 7 which is encompassed by the duct. The first fluid path 3 is shown perpendicular to the cross section of the tube wall 30.

With reference to Figure 1 and 2, the tube wall 30 is provided with a large number of small orifices 80 (i.e., holes or openings) distributed along and about a thin walled contactor tube 10. As will be explained in more detail below, the first fluid 901 is directed to flow along the first flow path 3 through the tube 10 and then through a third flow path 5 formed by the orifices 80, out into the second flow path 4, which is defined by the fluid duct 130. A second fluid 904 is directed through the duct 130 along the second flow path 4 such that the first fluid 901 and second fluid 904 are mixed together within the duct 130. The second fluid path 4 is shown parallel to the cross section of the tube wall 30, though it may be at any angle to that tube wall.

As will be explained in more detail, below, in some embodiments, users create a differential ejection pressure across the perforated tube 10 sufficient to force the first fluid 901 through orifices 80 and form drops (or bubbles) 902 or micro-jets 903 of the first fluid 901 in the second fluid 904. In modified embodiments, the second fluid flows across the orifices 80 to entrain the micro-flows, micro-jets, drops or bubbles of the first fluid 901 delivered with a desired differential ejection pressure into that second fluid 904.

It should be appreciated that although dictionary definitions of "tube" refer to a "cylindrically walled member". Applicants do not intend for tube to have such a limited definition. Instead, Applicant has used "tube" to refer to a distributed member which has an inner surface forming a passage that defines a first flow path to deliver a first fluid. The distributed

member is often an elongated walled member. It may have a variety of cross-sectional shapes as will be apparent from the description below. The distributed member comprises orifices which are often round but which may be elongated or form slots etc.

8.2.1 Number of Orifices or Jets

Conventional systems typically only use a few orifices in a plate or at the end of an injector. In contrast, users provided one or more contactor tubes with a lineal orifice density of at least hundreds of orifices per meter of tube length, more preferably with thousands of orifices per meter of tube length, and still more preferably optionally tens to hundreds of thousands of orifices per meter of tube length depending on the application. In other words, with respect to Figure 1 and Figure 2 the lineal density of the orifices 80 on the tubes 10 may range from about a few orifices per centimeter to hundreds or thousands of orifices per centimeter of tube length.

The orifices 80 are distributed across the second flow path 4 to achieve a desired transverse flow distribution of the first fluid 901, or flow ratio profile of the first fluid flow divided by the mean first fluid flow, preferably on a mass basis, or alternatively on mol or a volume basis. The flow distribution and orifice distribution provide a desired mixing distribution of the two fluids. For example, to produce a uniform ratio of second fluid to first fluid flow, the orifices 80 are distributed with a substantially non-uniform distribution across the second flow path 4 within the duct 130 to accommodate the non-uniform flow of the second fluid. In such configurations, the orifices are configured in arrays of perforated tubes 10 across the flow path 4 thereby distributing hundreds and preferably thousands to hundreds of thousands of orifices or more across the second flow path 4.

Typical ranges of orifice specific number density (number of orifices per duct cross sectional area) are shown in Table 1 Orifice Specific Number Density for typical ranges of orifice lineal density along contactor tubes and for typical ranges of tube to tube spacing.

Table 1: Orifice Areal Density (Number of Orifices/m^2)

Lineal Density (Orifices/meter)	Tube Spacing Gap (mm)					
	100	30	10	3.0	1.0	0.10
30	*300*	*1,000*	*3,000*	10,000	30,000	300,000
100	*1,000*	*3,333*	10,000	33,333	100,000	1,000,000
300	3,000	10,000	30,000	100,000	300,000	3,000,000
1,000	10,000	33,333	100,000	333,333	1,000,000	10,000,000
3,000	30,000	100,000	300,000	1,000,000	3,000,000	30,000,000
10,000	100,000	333,333	1,000,000	3,333,333	10,000,000	100,000,000

Ranges of Duct to Orifice Area ratios are shown in Table 2 for a range of orifice specific number density, the orifice sizes. This demonstrates the very wide range of duct to orifice areas that can be configured with various embodiments of the direct contactor arrays.

Table 2: Mean Duct to Orifice Area (m^2/m^2)

Orifice Areal Density (No. of Orifices/m^2)	Area of each Orifice (mm^2)			
	7.85E-07	7.85E-05	7.85E-03	7.85E-01
10,000	7.9E-09	7.9E-07	7.9E-05	7.9E-03
30,000	2.4E-08	2.4E-06	2.4E-04	0.024
100,000	7.9E-08	7.9E-06	7.9E-04	0.079
300,000	2.4E-07	2.4E-05	2.4E-03	0.236
1,000,000	7.9E-07	7.9E-05	7.9E-03	0.785
3,000,000	2.4E-06	2.4E-04	2.4E-02	2.4
10,000,000	7.9E-06	7.9E-04	7.9E-02	7.9
30,000,000	2.4E-05	2.4E-03	2.4E-01	23.6
100,000,000	7.9E-05	7.9E-03	0.785	78.5
	0.001	0.01	0.10	1.0
	Orifice Diameter (mm)			

8.2.2 Tube Supports

As shown in Figure 1, the distributed contactor array 260 may include one or more structural supports 37 to support the distributed tubes 10 against the bending forces created by the cross-flow of the second fluid 904 along the second flow path 4 through the duct 130. In some embodiments, as shown in Figure 68, users preferably make these external stiffeners or

tube supports 37 from thin streamlined shapes aligned with the flow. This reduces the pressure drop and pumping power attributed to these stiffeners.

The supports 37 are preferably configured to provide sufficient flexure to accommodate any differential thermal expansion during operation and are designed to accommodate vibration, pressure oscillation, gravity, acceleration and other forces using techniques well known in the art. In some embodiments, the distributed tubes 10 may form in part the structural supports 37.

8.2.3 Differential ejection pressure with numerous orifices

With a large number of orifices, a large cumulative cross-sectional area of orifices 80 is provided for the first fluid to flow through. An advantage of this arrangement is that in some embodiments a large differential ejection pressure is not required to deliver the first fluid 901 through the orifices 80 into the second fluid 901. e.g., compare the relevant art which often uses pressures of about 750 bar to 3000 bar (about 10,000 psi to 40,000psi).

In contrast, in one embodiment, a relatively low positive differential (e.g, about 0.001 bar to 750 bar or about 0.01 psi to 10,000 psi) pressure may be used to force the first fluid 901 within the tube 10 out through the orifices 80 to form drops 902 (See, e.g., Figure 3). An advantage of this embodiment, is that the low pressure distribution method reduces the pumping costs typically required in conventional systems which use conventional very high positive differential ejection pressures with a few orifices.

In various embodiments, (referring to Figure 2) the differential ejection pressure is increased to expel the first fluid through an inner orifice opening 88 at the inner surface 6 of the tube wall 30, through the orifice 80 along the third fluid path 5 through the outer orifice 90 at the outer surface of the tube wall 30 and into the second flow path 4. This forms a large number of short jets or micro-jets 903 through numerous orifices 80 into the second flow path 4. The orifices may be further designated as axial orifices 84 along the duct axis, radial orifices 85 perpendicular to the duct axis, or angled orifices 86 at other angles to the duct axis.

Alternatively, the full range of differential ejection pressure is sometimes used to increase fluid delivery turn-down ratio (such as in Figure 2). That is, increase the effective operating range of fluid delivery by the distributed contactor system by providing a wide range of pressures.

8.2.4 Uniform or Prescribed Distribution through many Orifices

As mentioned above, the distributed contactor system 2 preferably includes perforated tubes 10 with a large number of small, orifices. It is also advantageous to distribute these orifices 80 across the second flow path 4 to efficiently mix the first fluid 901 flowing through orifices 80 with the second fluid 904 flowing across those orifices 80. This arrangement causes more efficient distribution and mixing of the fluids 901, 904. This results in more locally homogeneous compositions which may vary in composition as desired transversely across the duct.

In various embodiments, the distributed fluid contactor 2 may be used distribute drops of a first liquid into a second gas, distribute a first gas into a second gas, distribute a first liquid into a second liquid, or distribute a first gas (e.g., bubbles) into a second liquid. That is, the first fluid 901 may be a liquid, gas or a combination of liquid and gas (e.g., water droplets, mist, solution, suspension, fluidized powder, nucleated bubbles of vapor in a liquid, etc.). Similarly the second fluid 904 may also be a liquid, gas or combination of liquid and gas (e.g., water droplets, mist, nucleated bubbles of vapor in a liquid, etc.) In some configurations, the second fluid 904 may comprise a fluidized powder.

8.3 Numerous Orifice Array Configuration Linear array

As mentioned above, rather then a high pressure spray from one or a few nozzles, in some embodiments the distributed contactor system 2 utilizes large number of orifices 80 in an array along the tube wall 30 to provide a more effective, uniform or desired mixing of the first fluid 901 emitted from the perforated tube 10 with the second fluid 904. With reference to Figure 13, the orifices 80 have a diameter d at the outer tube wall 7, and are formed in the tube wall 30 having a wall thickness "**t**". The orifices 80 are spaced at intervals "**h**" along the tube wall 30, and have a gap "**g**" between orifices. (Note, h = d + g.) The tube 10 has an inner radius Ri and outer radius Ro (as shown in Figure 34) and a outer diameter D (as shown in Figure 27.)

When forming drops by gravity or fluid pressure extrusion, pendant drops are formed with a nominal diameter "**d'**" which are typically of the order of twice the diameter "**d**" of the orifice or hole 80. Thus, holes of about 2 micrometer (μm) diameter nominally create droplets of about 4 micrcometer (μm) in diameter at low pressures or velocities.

As will be explained below, the arrangement of the orifices 80 on the tube 10 may be varied in a variety of ways to achieve different results. For example with reference to Figure 7, in some embodiments, the first fluid 901 flows along fluid path 3 and then through substantially uniform orifices 80 which are arranged in one or more lines on the tube wall 30 out to the fluid path 4. They may be configured as "radial orifices" 85 perpendicular to the second flow path 4, or as angled orifices 86 at some oblique angle to the flow path 4.

8.3.2 Column or Arc

In other embodiments, the orifices 80 are distributed in a columns or arcs 93 about the tube wall 30 as shown in the exemplary embodiment of Figure 8. In such an embodiment, the first fluid flowing from the first fluid path 3 through a column 93 of orifices 80 in line with the second fluid flow 904 will create a number of in-line parallel sprays traversing the second fluid path 4 of the second fluid flow. The cooperative in-line spray effect will desirably reduce the rate the downstream sprays are diverted by the flow. This advantageously enables sprays of fine drops to penetrate further across the transverse flow. Preferably many orifices are arranged in a column or arc about the tube wall 30 to create many smaller more uniform drops while projecting them further across a flow than is possible with individual sprays with similar differential ejection pressures.

8.3.3 Curvilinear Spatial Orifice Array

In other embodiments, users preferably form a spatial array of orifices by creating an curvilinear array comprising lines, columns, arcs, or other curvilinear orientations of orifices.

Hexagonal orifice array: For example, as show in Figure 14, to provide a maximum orifice spatial concentration, in some embodiments, the orifices 80 are arranged in a hexagonal array 91 with orifice spacing h from each neighboring orifice 80. The orifice array may further be oriented at some angle alpha to the second fluid flow path 4 between zero and 60 degrees. Alpha is preferably about 30 degrees as shown in Figure 14. At low pressures and flow velocities, pendant drops typically form with diameters d' about double the diameter d of the orifices 80 from which they are formed. The orifices 80 are preferably spaced at intervals h such that the drops have sufficient gaps g' between them to prevent coalescence. In some embodiments, the

orifices are preferably spaced at a distance h apart that is preferably at least about three times the orifice diameter d to provide a gap g' of at least about half the drop diameter d' between drops.

Cartesian orifice array: In some embodiments, as shown in Figure 15, the orifices 80 are arranged in one or more Cartesian or rectilinear orifice arrays 92 with an angle alpha from the flow path 4 of the second fluid 904. In Cartesian arrays, alpha is between zero and 90 degrees, and is preferably about 45 degrees as shown in Figure 15. The orifices 80 of diameter d with orifice spacing h in orthogonal lines, giving gaps g between orifices. As before, the orifice spacing h is preferably of the order of at least three times the orifice diameter d to give a gap g between holes of twice the orifice diameter to reduce probability of drop coalescence.

Areal Orifice Density: As mentioned above with reference to Figures 14 and 15, in some embodiments, users preferably configure the orifices 80 or holes in an hexagonal array for greatest areal hole density and in other embodiments, these orifice or hole arrays are formed into a Cartesian pattern. For a hole spacing of h, a hexagonal array will give $2/(h^2 3^{0.5})=1.1547/h^2$ holes per unit area or 15.5% greater areal density (holes/area) compared to a Cartesian array with areal density of $1/h^2$.

8.3.4 Orifice spacing

To prevent drop coalescence during formation, the hole interval h is preferably significantly greater than the drop size formed. It is preferable to provide significant gaps "g'" between drops, to prevent droplet coalescence.

With reference back to Figure 14, in some embodiments, the holes are arranged in a hexagonal array with hole spaced at intervals "h" preferably at least about 300% to 400% of the hole diameter d. For example, with about 2 μm diameter holes forming about 4 μm diameter drops, the holes are spaced at intervals of at least about 6 μm (i.e. drops of 3 x 2 μm in size preferably spaced at least about 3 x 3 μm apart). Similarly with reference back to Figure 15, some embodiments involve holes arranged in a Cartesian or rectangular array with similar ratios of hole spacing to hole diameter.

8.3.5 Columnar or Rectangular Arrays

In some embodiments, as shown in Figure 8, the orifices 80 may be arranged orifices as multiple discrete arrays 93. The orifices 80 may be arranged in columnar arrays 93, wrapped about the tube 10. In other embodiments as shown in Figure 45, the orifices may be arranged 80 in rectangular arrays of orifices, with the arrays spaced along the tube 10.

8.4 Spatial Orifice Density In various embodiments, users of the fluid contactor 10 (see Figure 1) need or desire to configure and control the spatial composition distribution or ratio of the flow of the second fluid 904 flowing across the perforated tubes 10 to the flow of a first fluid 901 flowing through the tubes 10. To do so, users preferably adjust the orifice specific density (local average of the total orifice area over a local tube section in the perforated tube 10 relative to the corresponding cross-sectional area of the second fluid duct 130 at that location. This measure can be refined by accounting for the reduction in actual jet cross sectional area as it leaves the orifice. E.g. in the range of about 80% to 99% of the orifice exit area depending on the geometry and fluid parameters.) They preferably evaluate or model and account for the velocity and mass spatial distributions of the second fluid flow such as radially to the duct to quantify the non-linearity in the flow. These factors permit much lower differential ejection pressures and results in more uniform mixing than conventional methods. This method is contrasts with using a few orifices with high pressure differences as is typical in the prior art.

This design parameter is approximately equal to the effective orifice area per length of contactor tube divided by the tube to tube spacing h. (Note that this may count multiple rows of orifices along the tube and orifices of differing size.) The effective orifice area is obtained by the gross cross-sectional area of the orifices adjusted for net fluid flow area exiting the orifice due to the necking down of fluid flow within the orifice variously caused by roughness, geometry, turbulence, cavitation and/or entrained bubbles.

Detailed designs will involve other parameters as desired or needed such as orifice size, orientation and configuration, the pressure difference across the tube wall, the pressure drop of the second fluid flowing across the tubes, the relative fluid densities, viscosities, surface energies, pressures, temperatures, tube configurations and relative positions etc. These may further use full CFD modeling to best position and orient the orifices.

8.4.1 Axi-symmetric Flow Distribution for Uniform ratio of fluid flows

As is well known in the art, the fluid flow in ducts commonly displays a substantial velocity distribution being faster near the duct axis 133 or center and slower near the duct wall 132 (see Figure 1) relative to the mean flow. These range from highly parabolic flow profiles for laminar type flows to more truncated flow profiles for turbulent flows. See for example, Figure 18, Figure 19 and Figure 20 which illustrate examples of skewed parabolic flow profiles such as found within or after compressors.

In one embodiment, the contactor is configured to achieve a uniform or prescribed ratio of the second fluid to first fluid across a duct with such a non-uniform velocity profile. Referring to Figure 18 and Figure 20, to achieve a uniform ration, the first fluid 901 is preferably delivered with a transverse spatial distribution proportional to the mass flow transverse spatial distribution of the second fluid 904 across the duct. In such an embodiment, the tubes 10 and the orifices 80 may be distributed across the duct 130 to provide the desired axi-symmetric flow distributions.

For example, Figure 16 illustrates an embodiment of a fluid contactor 2 comprising a circular contactor array 265 within a circular duct 144. In this embodiment, the fluid contactor 2 includes contactor tubes 10A-C that are formed into circular arrays 265, which may have axi-symmetric orifice configurations where the orifice lineal density along each contactor tube 10A-C, and specific orifice spatial density across the duct (locally averaged net orifice area per duct cross- sectional area) (not shown) varies radially across the circular contactor array 265. External tube supports 37 are added to stiffen the circular array 265 against the drag of the axially flowing second fluid 904 entering the duct entrance 134.

In a similar manner, the embodiment illustrated in Figure 1, the director contactor 2 includes contactor tubes 10 formed into the contactor array 260 shown as a downstream increasing concave tube array (similar to a conical array in the "horn" configuration) with an axi-symmetric orifice configuration. Figure 68 depicts fluid contactor 2 with contactor tubes 10 arranged in a "funnel" conical array 264 that comprises perforate tube arcs (or curvilinear sections) 21. Each tube arc 21 may be provided with a prescribed orifice spatial density for each of the perforated tubes 10. E.g., the spatial orifice density is uniform at a given radius, or distance

from the cone apex to achieve the desired ratio orifice spatial density to transverse area that varies in proportion to the second fluid flow distribution as desired.

8.4.2 Radial variation in ratio of fluid flows

With continued reference to Figure 16, in some embodiments, to obtain a prescribed radial variation or profile in the ratio of fluid flows, users preferably vary the net orifice specific spatial density radially from the axis to the circumferential wall of the fluid duct 130. For example, the tubular array 265 comprises a first inner ring contactor 10A, an outer ring contactor 10C and preferably at least one intermediate ring contactor 10B. A manifold 240 delivers the first fluid 901 to at least one spoke like sub-manifold 254 extending from the outer ring 10C, to the intermediate ring 10B, and to the inner ring 10A, so as to provide a fluid path between the rings 10C, 10B and 10A.

Each contactor ring or perforated tube 10A-C comprising orifices 80 having an net specific orifice spatial density of the net area of orifices divided by the relevant cross-sectional duct area. i.e. the relevant area is the mean tube to tube spacing multiplied by the mean incremental orifice spacing distance along the tube 10 at that location. Furthermore, in some configurations the lineal orifice density varies from one side of each tubular ring 10A-C to the other side to adjust the net orifice density in the radial direction transverse to the duct axis or perpendicular to the tube arcs. In such cases, the area is the half the tube to tube spacing on that side of the arc multiplied by the orifice spacing along that side of the tube. Users preferably adjust the net spatial orifice density along each contactor ring 10A-C to achieve a radial distribution of spatial orifice density that varies radially as desired in a circular fluid duct 144, an elliptical fluid duct (not shown) or annular fluid duct 146 (such as shown in Figure 52).

8.4.3 Circumferential variation in ratio of fluid flows

In some embodiments, to obtain a desired circumferential profile (or "pattern") in the ratio of fluid flows such as around an annular duct, users preferably adjust the orifice spatial density in the circumferential direction around the fluid duct 130. E.g., in the embodiment of Figure 16, the contactor 2 has a desirably uniform circumferential spacing of orifices 80 along circular contactor arcs 10A-C around the circular array 265 in the circular fluid duct 144. Similar

configurations can be arranged around an cylindrical tube array 270 or an annular tube array in annular fluid duct 146 (See. Figure 52.)

8.4.4 Transverse variation in ratio of fluid flows

Figure 17 illustrates a contactor system with a rectangular array 266 of linear contactor tubes 10, users can vary the spatial density of orifices from one tube to the next tube to obtain variations in at least one transverse direction across the duct 130. Such an embodiment is particularly useful in rectangular ducts (such as in Figure 53). In Figure 17, the direct contactor system includes orifices 80 that are spaced along the contactor tubes 10 to increase and then decrease the net orifice spatial density as the rectangular fluid duct is traversed along one transverse direction.

8.4.5 Spatial variation in ratio of fluid flows

To achieve a multidimensional spatial variation in fluid ratio, users preferably vary both the spatial density of orifices along each tube in one dimension (or parameter) as well as the spatial density or variation in a second direction (or parameter) such as from tube to tube across the array in some configurations. E.g., along the major transverse coordinates in cylindrical or Cartesian coordinates.

For example, in rectangular arrays 266 as shown in Figure 17, the net orifice spatial density may be varied in both directions transverse to the duct axis in some configurations. In this manner, both the horizontal and the vertical transverse spatial density of orifice 80 are configured to accommodate the horizontal and vertical transverse velocity distributions of the second fluid 904 flowing through the rectangular duct 145 to account for the variations in transverse profiles due to the effect of boundary layers and/or turbulence within the duct.

8.4.6 Varying spatial fluid delivery profiles

To dynamically vary spatial fluid delivery distributions and profiles, users adjust the differential ejection pressure distribution along the longitudinal axis of the contactor tubes by adjusting the pressure in one or both sub-manifolds 254 or manifolds 240 to which the contactor tubes 10 are connected. The pressure is preferably adjusted using one or more pressure flow modulator 370 or sub-manifold valve 233.

8.5 Orifice Size

8.5.1 Magnitude of Orifice Size

In various embodiments, users preferably form the orifices 80 on the fluid contactor (See Figures 1 and 2) may be formed with a diameter that is about 1% to about 30% of the thickness of the tube wall according to the hole size required or desired and the hole forming technology used and the desired jet penetration and consequent differential ejection pressure required.

As examples, in other embodiments, the contactor 10 may have 2 micrometer diameter holes to about 60 μm holes in 200 μm thick walls of the thin-walled tube 10. In other embodiments, the contactor 10 may have about 0.3 to 10 micrometer diameter holes in an ultra-thin walled sheet or foil etc. of about 30 micrometer thick. For applications involving direct contactors with physical changes such as condensing, the contactor may have orifices ranging from 50 micrometers to 5 mm, and preferably from 200 μm to 2 mm.

8.5.2 Orifice Size Uniformity

Orifices 80 of differing size typically create drops (or bubbles) of differing size, given sufficient pressure to emit such drops. To form drops of uniform size and at a uniform rate, the orifices 80 are preferably provided with uniform dimensions within a prescribed statistical distribution parameter. For example, with a relative standard deviation (RSD) < 0.1, preferably < 0.01 and more preferably with the RSD < 0.001. Of course, other suitable RSDs may be efficaciously utilized, as needed or desired. Figure 7 illustrates one such embodiment, which utilizes radial orifices 85 and angled orifices 86 of uniform orifice size.

8.5.3 Pressure drop adjusted orifice size

Liquid flow within small diameter tubes 10 may cause a significant pressure drop along the tube. Conversely, any heating (or cooling) of the fluid along the tube will reduce (or increase) the surface tension. To compensate for such effects, as shown schematically in Figure 20, where needed, the orifice size 80 can be increased or decreased along the contactor tube 10 according to the distance away from the manifold 240 or sub-manifold 254 and the change in temperature, to compensate for this increasing pressure drop or heating change in surface energy.

8.5.4 Stepped Orifice Sizes

In other embodiments users make the orifice gradations in substantially discrete sizes. The orifices may be arranged arranged in discrete sizes such that the drop size formed or micro-

jet diameter and drop size distribution are significantly varied as desired. Figure 9 illustrates one embodiment which utilizes orifices of three sizes. The orifices are further configured to increase in size and then decrease in size progressively along the longitudinal axis of the tube 10. I.e. orifices with smaller openings 89 are shown followed by medium sized orifices 80 and orifices with larger openings 87, which are followed by medium orifices 80 and then small orifices 89.

With such configurations in low flow with short penetration distances, users may control which orifices through which drops are expelled by controlling the positive differential ejection pressure applied. Accordingly, users can cause drops to be formed from larger sized orifices and not from smaller orifices by controlling the differential ejection pressure of the first fluid relative to the second in relation to differential ejection pressure required to overcome the interfacial surface energy relative to the given orifice size.

8.5.5 Graded Orifices

In some embodiments where users need or desire to control drop size and location of drops, the direct contactor 2 includes graded orifice arrays. The orifices 80 may have diameters changing in curvilinear fashion with a prescribed systematic method. In one embodiment, the orifice area may be systematically varied e.g., the diameter of the orifices 80 is varied as the square root of the desired orifice area. The orifices may be formed using lasers or other suitable orifice forming methods. The desired orifice area in turn is preferably configured as a function of spatial location. In this manner, users can control the positive differential ejection pressure across the tube to control the portion of the orifices through which fluids or liquids flow.

They similarly configure gradation in orifice areas and diameters for arithmetic, geometric, polynomial or other desired spatial functions E.g., by varying the orifice diameter as the half power of a transverse dimension, user obtain a generally linear variation in drop size along that dimension. Similarly, varying the orifice diameter according to the first power of a transverse direction gives a generally parabolic variation in drop size along that direction etc.

8.5.6 Tailored Orifice Distribution

Flow through an orifice is generally proportional to the square root of the differential ejection pressure across the orifice. A 100:1 turn down ratio of flow rate would conventionally or

typically require a pressure difference of 10,000:1. To compensate for this phenomena, in some embodiments, the direct contactor may be configured to utilize the effect that at low differential ejection pressures, orifices of different sizes will selectively pass fluid through some passages and not thru others. Accordingly, the contactor may be configured such that the orifices are varied with respect to both their size distribution or profile, number distribution, lineal net jet area distribution, and/or spatial net jet area distribution to obtain a desired flow rate versus differential ejection pressure distribution while achieving a prescribed micro-jet or drop size distribution. For instance users can obtain a linear, quadratic or other variation of flow vs differential ejection pressure instead of (or in combination with) the default square root relationship. This can expand the relative control at low differential ejection pressure. This can be used to expand the overall turndown ratio.

8.5.7 Configuring Orifice Size Distribution

In other embodiments, users form orifices with various prescribed sizes to correspondingly form drops or micro-jets of various sizes or with more desired transverse distribution of a measure of drop size such as the Sauter Mean Diameter (SMD), along one or more of the axial, first or second transverse directions.

8.5.8 Non-curvilinear, Random & Pseudo-random Arrays

Random or non-curvilinear arrays: In some embodiments, the orifices may be formed in a random spatial array in a tube wall as needed or desired. (Not shown.) E.g., In some configurations, users randomize the location of orifices. The size of orifices is randomized in some configurations. In other variations, both the location and size of the orifices is randomized. In situations where regular orifice arrays and periodic pulsing cause pressure oscillations, these oscillations might advantageously be reduced by shifting to or providing such randomized arrays of orifices.

Pseudo-random arrays: In another embodiment, the orifices form pseudo-random or non-curvilinear arrays by combining "random" placement and/or size of orifices with net variations in the net orifice spatial density. I.e. the net area of orifices per unit cross-sectional area of fluid duct. These methods include varying the net orifice spatial density as desired or

needed. E.g., increasing and then decreasing the spatial density transversely across the fluid duct 130. An example of such an embodiment is illustrated in Figure 10.

Non-Curvilinear arrays: Of course, in other embodiments, the orifices may be oriented other non-curvilinear arrays other than those explicitly described, as desired or needed.

8.5.9 Orifice Cone Angle

In some embodiments, users adjust one or both of the thickness of the tube wall and the orifice diameter to adjust the thickness to diameter ratio (t/d). This in turn is adjusted to achieve desired micro-jet spray angle which varies by this ratio.

8.5.10 Generalized Orifice Configuration

Of course, in other embodiments, the orifices may be located, spaced and/or sized in other suitable manners with efficacy, to achieve net spatial densities or other parameters or to avoid certain configurations as desired or needed.

8.6 Location of Orifices With reference to Figures 1, 13 and 23, in some embodiments, users wish to eject drops or jets (or bubbles) of a first fluid 901 through the orifices in the tube and distribute them into a second fluid 904 (gas or liquid) flowing across the tube in one or more desired transverse distributions of first fluid flow, or transverse profiles of flow ratio of the second fluid to first fluid across the tube to tube gap G. In some configurations, users inject drops of the first fluid into a static fluid or into a vacuum. For example, the orifices are configured uniformly in some configurations to provide a uniform first fluid transverse distribution. In still other embodiments, users inject drops (or bubbles) of the first fluid against the second fluid flow. This is preferably where gravity, centrifugal acceleration or an electrostatic field exists or dominates to urge or propel the drops (or bubbles) against the flow.

8.6.1 Circumferential angle of orifices

As shown schematically in Figure 23, users configure angled orifices 86 at varying angles to the duct axis giving differing exit angles for the micro-jets 903 as the exit. The micro-jets 903 follow nominally parabolic trajectories starting at the initial ejection direction, and turning towards asymptotic to the transverse second fluid flow direction or second fluid path 4. (This flow may be perturbed by turbulence downstream of the tubes which forms alternating vortices parallel to the tube that spin off with the second fluid flow, depending on velocity.) The

penetration distance with time depends on the relative momentum of the first fluid jet relative to the second fluid jet. Consequently, by varying the circumferential angle of the longitudinal axis of the angled orifice 86, users achieve varying jet penetration distances of the micro-jets 903 across the gap. Similarly laminar jets will form fairly uniform drops and position those at differing distances across the tube to tube gap. By varying the transverse distribution along the longitudinal axis of the tubes of this circumferential orifice angle, users achieve varying transverse distributions of the jet penetration distance across the tube to tube gap.

As shown in Figure 23 and Figure 27, in some embodiments, users preferably locate radial orifices 85 substantially perpendicular to (normal to or at 90 deg to) the direction of the second fluid flow path 4 across the tube 10 (similar to the duct axis with planar arrays). Such transverse orientations achieve a higher transverse jet penetration than jets 903 oriented radially more downstream or upstream, as conceptually shown in Figure 23. In other configurations, users preferably configure angled orifices 86 about 135 degrees from the downstream looking duct axis. I.e. 45 degrees from the upstream looking axis. This orientation gives about the highest degree of mixing of the two jets.

8.6.2 Orifice circumferential location

Again with reference to Figure 23, in some embodiments, users position orifices 80 (also shown as angled orifices 86) at different circumferential locations around the tube 10 resulting in different locations relative to the duct and the second fluid flow. This positions orifices 80 at different transverse distances relative to the tube to tube gap and axial second fluid flow. It also positions orifices with differing axial locations relative to the duct or the tube axis.

8.6.3 Combined Orifice angle, radial location and size

With reference to Figure 23, in some configurations, users individually configure the position of the orifice 86 circumferentially around the tube 10, the angle of attack of the orifice longitudinal axis to the duct axis and the diameter or size of the orifice. These measures provide four degrees of freedom in configuring the degree of penetration of the micro-jets.

In some configurations, users set the circumferential angle of the longitudinal axis of the orifice to one angle, while separately varying the orifice circumferential location around the tube.

This adjusts the transverse location of the jet relative to the tube to tube gap while keeping the same angle of attack between the jet 903 and the duct axis. Conversely, users may orient the orifices with differing circumferential angles while maintaining the same circumferential location around the tube.

Orifice positions and orientations are preferably adjusted according to the relative speed of the transverse flows and tube dimensions. These parameters will vary according to how laminar or turbulent the flow becomes and affect the flow velocity profiles.

In accordance with some embodiments, by forming uniform orifices and forming laminar jets, users form fairly uniform drops (or bubbles) of the first fluid that will penetrate a fairly uniform distance into the second fluid.

8.6.4 Orifices at tube corners

For very low flow rates of the first fluid, drops may not be ejected as the fluid flows out from the tube, but might "dribble" or "weep" across the tube surface, wetting the tube. Certain flows of the second fluid flowing transversely across the contactor tube 10 could also influence such wetting. Drops could then aggregate resulting in larger drops breaking off the tube.

To reduce the tendency for drops to "dribble" or "weep" across the outer tube surface at low pressures and with turbulence, in some embodiments as shown in Figure 41 users preferably form the tube wall 30 into a generally hemispherical to triangular cross-sectional shape comprising a more "bluff" downstream section and then place orifices 80 near the downstream corners. This may increase the ability of the drops to break away at low flows, compared to orifices located normal to the fluid flow in an oval tube. In modified embodiments (not shown), users form the tube into a diamond or rotated square shape or similar polygonal shape and locate orifices at the corners.

8.6.5 Orifice axial location

With reference to Figure 8 and Figure 11, by configuring orifices 80 in a line (column) or arc around the tube in some configurations, users form a columnar multi-orifice spray where drops collectively travel farther than they would in a jet from an isolated orifice. This changes the distance the drops or micro-jets travel into the transverse flow. To utilize or compensate for this

effect, in some embodiments, users systematically align orifices or displace orifices in incremental locations axially along a tube as well as around the tube. Thus, in some embodiments, users preferably position the orifices in arcs that curve both around and along a tube to distribute drops across the flow. (See e.g., Figure 23 described above)

8.6.6 Orifices in tube ends

As shown in Figure 12, in other embodiments, users form orifices 80 in the end of a tube 10, whether closed off by hemispherical (illustrated), flat (not shown) or other surfaces. The orifices may be configured as radial orifices 85 pointing transverse to the flow, axial orifices 84 pointing along the duct axis, or angled orifices 86 pointing to an intermediate angle.

8.7 Orifice Configuration, Spacing and Orientation In various embodiments, users preferably adjust the orifice spacing, circumferential and longitudinal orientation, circumferential and longitudinal position, and array configuration to position and mix drops and/or micro-jets of the first fluid into a second fluid with desired transverse distributions along one or more of the axial, first and second transverse directions. These are detailed as follows.

8.7.1 Conical Orifice Orientation

Laser drilling typically forms truncated conical holes through a tube wall, forming a larger orifice opening nearest the laser and a smaller orifice opening farthest away from the laser. With reference to Figure 5, to reduce hole blockage and facilitate cleaning, the smaller diameter orifice openings 89 are preferably oriented as the inward orifice 88 at the tube inner surface 6 so that the hole size increases outwardly to the outward orifice 90 at the tube outer surface 7. Holes 80 with this outwardly opening configuration can be laser drilled directly into tubes 10 from the outside.

Where fluid differential ejection pressure is sufficient to cause the fluid 901 to cavitate as it flows through the orifice 80, the fluid jet forms an outwardly reducing flow cross section resulting in a jet exiting the outer orifice 90 that is significantly smaller than the smaller orifice 89 even though it forms the inner orifice 88 at the tube inner surface 6.

With reference to Figure 6, if the smallest possible holes or orifices areas 89 are needed on the outer tube surface 7, users preferably form orifices through strips which become the thin

wall sections 32. E.g., using lasers, etching or mechanical drilling etc. They then form the perforated strips into tubes 10, aligning the smaller diameter orifices 89 as the orifice outer openings or exits 90 at the tube outer surface 7 of the strip or tube wall 32 and the larger orifice diameter 87 with the inward surface 6.

8.7.2 Orifice Array Width

With reference now to Figure 43, in some embodiments, users preferably form the orifices or holes into arrays of width W. With two arrays, the collective width 2W is about equal to about 50% to about 100% of the diameter D of the contactor tube 10. In the illustrated embodiment, these orifices 80 are positioned into two arrays preferably positioned on either side of the tube 10 with a central blank section near the downstream side of the contactor tube 10. The central blank section is preferably about 20% to about 140% the diameter of the contactor tube.

With continued reference to Figure 43, the exemplary embodiment, two arrays of about 626 holes 80 across are made, each forming perforated strips about 3.75 mm wide on either side of a central solid strip about 1.5 mm wide. This creates a perforated strip circumference of about 7.5 mm with about 1252 holes. In this embodiment, the array width of about 7.5 mm is about equal to the lateral tube spacing of about 7 mm.

In embodiments having compound tubes which will be described below this gives a total downstream tube section circumference of about 9 mm. In such compound tubes, users preferably allow at least another 0.5 mm to 1.0 mm on each edge to attach to the stiffening tube. This results in a total strip width of at least about 10 mm to about 11 mm to form these downstream tube sections. Alternatively, as shown in Figure 46 the downstream section can be configured wider to also wrap around the upstream structural tube section.

Note that these dimensions are illustrative taking a convenient thin walled tube. Similar effects are obtained in selecting larger or smaller dimensions. Users may select the tube size, shape and spacing according to the orifice diameter and maximum micro-jet distance desired or needed relative to the tube spacing.

8.8 Orifice Angular Orientation to 2^{nd} Fluid Flow In some embodiments, in addition to, or instead of, positioning orifices transversely around the tube, users preferably orient

the orifices at various predetermined or pre-selected angles relative to the second fluid flow path to adjust the terminal position of the fine drops injected into the transverse flow. By such measures, users form drops of substantially uniform size and position them fairly close to some desired distribution across the transverse fluid flow in configurations using low differential ejection pressures to create fairly laminar jets. E.g., uniform, or proportional to the gas velocity. Similarly with higher pressures, users form turbulent micro-jets oriented at different angles to deliver the jet into desired locations across the tube gap.

This technique or methodology is preferably further refined to compensate for the variation in velocity of the transverse flow across the gap between the tubes and for the changes in differential ejection pressure across tube wall due to the Bernoulli effect. Accordingly, in some embodiments, users preferably position drops between and along tubes to achieve fairly uniform number of drops of the first fluid per unit mass of the second fluid in the transverse flow.

8.9 Orifice Angular Orientation to Tube Axis With reference to Figure 30 through Figure 33, a jet of the first fluid 903 exiting the contactor tube 10 imparts momentum and turbulence to the second fluid 904 it penetrates. To increase the micro-turbulence in a desired fashion throughout the flow, in some embodiments users preferably orient the orifices at an angle to the tube axis other than 90 degrees to the tube axis (off of normal) i.e., off of a radius to the duct. This adds a momentum component transversely to the second flow's primary velocity vector.

For example, as shown in Figure 30, in some embodiments, users orient the orifices 80 in the same direction diagonally across the contactor tube 10. In some configurations, these contactor tubes 10 are aligned in parallel and offset resulting in orifices and micro-jets alternately opposed parallel to each other across the tube to tube gap. The alternating jets create numerous micro-vortices between their opposed jet edges with vortex axes parallel to the duct axis. This creates efficient thorough mixing.

As shown in Figure 31, in other embodiments, these tubes may be laid up in alternatingly in opposite directions, resulting in the orifices and micro-jets pointing the same direction in the tube-tube gap. This creates more macro swirl first in one transverse direction in one gap, and in

the opposite direction in the next gap. This results in vortices parallel to the duct axis being formed beneath each tube.

As shown in Figure 32, in other embodiments users form orifices in a chevron pattern on either side of the distribution tube. This results in the orifices and micro-jets pointing in the same direction at a given angle to the tube axis on either side of the tube 10. This can be visualized as the tube being the "backbone" of herringbone with the orifices pointing in the direction of the angled bones of the herringbone. With some configurations, these chevron or "herringbone" perforated tubes 10 are laid up parallel to each other. I.e. with the chevron orifices pointing in the same direction as shown for example in Figure 32. This results in the micro-jets on either side of a gap pointing in the same direction into the gap. This results in a general swirling flow to the entire flow about the duct axis.

In other configurations, as shown in Figure 33, the chevron perforated tubes are laid up alternatingly in opposite directions. This results in orifices and micro-jets opposing each other across a gap G. The orifices can be aligned so the micro-jets oppose each other by the spray width so that they alternate. These sprays will give some local mixing. They will also result in larger scale vortices parallel to and downstream of the contactor tubes.

8.9.1 Fluid-Droplet Vortex Mixing

In most embodiments, by providing a distributed tubular array of tubes, users generate vortices in the second fluid flow downstream of each of the tubes and manifolds. This distributed turbulence creates fairly uniform mixing of the first fluid flowing through the tube orifices with the second fluid flowing over the contactor tubes 10. The first fluid droplets and second fluid are mixed in the stream of vortices created immediately downstream of each tube.

8.10 Micro-Jet Penetration & Mixing As mentioned above, in various embodiments, users preferably design, configure and/or control the system so that the micro-jets and droplets of the first fluid exit orifices 80 on perforated tubes 10 and penetrate a desired distance into the adjoining tube to tube gap G.

8.10.1 Micro-Jet Penetration Distance

Users preferably use jet penetration correlations appropriate to the pressure of the second fluid, and the respective fluid velocities. As shown in Figure 21, users adjust the size of orifices 80 and the differential ejection pressure across the orifices to adjust the micro-jet penetration distances.

To calculate these penetration distances, users use the most effective appropriate correlations of jet penetration distances, such as summarized by Heywood, Internal Combustion Engines. For example, Holdeman (ASME, NASA 1997) has published jet penetration correlations. In integrated design calculations, the desired correlation of spray distance to orifice diameter is preferably normalized by the other side of the equation to obtain ratios near unity.

8.10.2 Turn-down Ratio, Mixing & Pumping Work

Referring to Figure 26 and Figure 27, for maximum turn down ratio, the maximum jet penetration is preferably configured about equal to or longer than the tube to tube spacing. Accordingly, as shown in Figure 26, the tip of one jet 903 penetrates across the gap G to near the adjacent contactor tube 10. This arrangement is also advantageous where users desire to increase mixing in which case they preferably configure the micro-jet penetration at peak design conditions to about equal to or greater than the tube to tube gap G.

It could also be designed to penetrate to about the far side of contactor tube 10, where the jet will extend downstream of the adjacent tube at peak flow conditions. The jet may be configured to spray across the tube into the next gap such as such as to 200% of the tube to tube spacing H. Opposing orifices are preferably displaced by about half the orifice spacing h. Consequently opposing micro-jets nominally fill the gap between the tubes when viewed from a plan view when the orifices are configured at the jet width of the sprays axially in line with that opposing jet wall.

The contactor tubes 10 may further be angled giving a varying tube to tube spacing H or tube gap G. As shown in Figure 26, the jet penetration may be adjusted to be some portion of the tube to tube gap G as this varies, by adjusting the orifice size, orientation and location.

As shown in Figure 28, in other configurations, where users desire reduced pumping work with relatively little change in flow, they preferably configure the micro-jets 903 to

penetrate about half way across the tube to tube gap G from both adjacent perforated tubes 10 in the maximum flow design conditions.

To further improve mixing in either of the arrangements of Figures 26 or 28, users preferably reduce the tube to tube gap G and increase the number of orifices and micro-jets. As shown in Figures 27 and 29, in some configurations, users angle some of the orifices 86 upstream, preferably at about 135 degrees upstream from the second fluid flow path to obtain about the highest degree of mixing.

To achieve these features, the orifice size, location and orientation, array configuration, gap between tubes, fluid differential ejection pressure, temperature, and external electrical field (as discussed further below) are designed or controlled relative to the flow, density and viscosity of the second fluid. The droplets will generally follow an approximately parabolic arc compounded by oscillating vortices formed by tubes.

For example, in the embodiments of Figures 26 through 29, tubes of about 4 mm diameter are positioned about every 7 mm giving about a 3 mm tube to tube gap. In this case, users preferably inject the droplets about 1.5 mm to 7 mm into the transverse diverging flow of the second fluid depending on the desired design operating parameters. Users may inject liquid or gas jets through orifices 80 of about 1 μm to about 200 μm in diameter in common applications depending on the dimensions and fluid properties etc. To achieve fairly small drops with fairly uniform mixing, users preferably configure orifices for about 5 μm to 40 μm. In cooling applications, these may increase to about 100 μm to about 2 mm or larger.

8.10.3 Tube to tube transverse fluid delivery distributions & ratios

With continued reference to Figures 26-29, to adjust the delivery distribution of the first fluid 901 delivered across the gap G between adjacent contactor tubes 10, users model the transverse fluid distribution for each micro-jet. They then evaluate the combined transverse fluid distributions or profiles by summing the distributions of the respective jets.

To achieve a desired degree composition of the second fluid 904 relative to the first fluid 901, users preferably evaluate the axial velocity of the second fluid 904 transversely across the tube to tube gap G. They then configure the orifice area, orifice orientation and differential

ejection pressure across the tube wall to configure the micro-jets across the tube to achieve the desired first fluid flows distribution relative to the second fluid flow distribution in the tube to tube or second transverse direction across the duct. These are configured such that the mean composite second transverse delivery distribution of the first fluid 901 is desirably proportional to the second fluid flow delivery distribution to achieve a desired ratio profile of the second to first fluid flows in this second transverse direction.

8.10.4 Uniform Tube to Tube Fluid Profiles

For the most uniform fluid distribution across the gap, users expect to configure the jets to penetrate about 35% to 45% of the tube gap G from either side. Similarly the jets penetrate about 60% to 90% of the tube gap G from each side of the gap providing overlapping jets and overlapping transverse fluid delivery distributions. In modified embodiments, users preferably provide a combination of penetrations using radial and upstream orifices to provide desired combinations of mixing and tube to tube flow profile of the first fluid relative to the second fluid.

To configure the delivered fluid 901 to more closely match a peaked velocity profile and fluid delivery profile of the second fluid 904 flowing between the tubes, users preferably configure the jets to penetrate about 40% to 50% of the tube to tube gap G from either side. Similar results are obtained by configuring jets to penetrate about 55% to 65% of the tube to tube gap G. Such configurations provide transverse fluid flow distributions and profiles between the tubes that are greatest about mid gap, and fall off towards the tubes.

8.10.5 Assymetric Tube-Tube Fluid Profiles

Users configure the circumferential orientation of the orifices about the tube to selectively direct the micro-jet spray to a desired portion of the tube to tube gap G. To achieve an asymmetric distribution, for example, they orient the orifices on opposite of the Gap and adjust the orifice areas and differential ejection pressure to deliver the micro-jet upstream (or down-stream) so that they are delivered asymetrically across the gap G.

With reference to Figure 24, users position two contactors 10 of diameter D to deliver a first fluid 901 through angled orifices 86 into the gap G between the contactors with a spacing H. The second fluid flows from the upstream inlet 134 to the downstream exit 136. For example,

users configure the orifice on the first or "upper" tube to deliver fluid about 25% to 50% across the gap from the lower tube to the upper tube as before. Then the orifice in the other tube is adjusted to about 160 degrees *** to deliver the micro-jet between 25% and 50% of the Gap distance from the lower to upper tube. This configuration positions both micro-jets from 25% to 50% of the distance across the Gap between the lower and upper tubes giving a highly asymmetric peaked fluid distribution.

With reference to Figure 25, in a similar fashion, users form an orifice on the "upper" side to deliver a micro-jet between 25% to 50% of the gap G from the "lower" tube to this "upper" tube. Similarly, they orient the orifices in the opposing tube (e.g., the "lower" tube) further upstream near 170 degrees to deliver the micro-jet between 0% and 25% of the gap from this "lower" tube to the "upper tube". Such a configuration provides fluid on one half of the tube to tube gap G but not on the other side.

These methods of asymmetrically orienting tubes on adjacent tubes about a Gap can be used together with methods of adjusting the orifice area and jet penetration distance to taylor the mean intra-gap fluid distribution to a desired asymmetric fluid delivery distribution. The angle of the orifice longitudinal axis to the tube longitudinal axis can similarly be varied to adjust the fluid distribution distance across the gap G.

8.10.6 Part load operations

With continued reference to Figure 26 through Figure 29, fluid flow generally varies as the square root of the differential ejection pressure across the contactor tube wall 30. However, varying the differential ejection pressure across the tube wall 30 also varies the jet penetration. When the jets penetrate the full gap under peak design conditions, they penetrate part way under part load conditions. (See, e.g., Figure 26 and Figure 27.) Similarly, when jets are designed for partial penetration at design conditions, the penetration is further reduced at off design conditions. (See, e.g., Figure 28- Figure 29.) In some configurations, users preferably evaluate the relative degree of mixing and the achieved ratios of second to first fluid as a function of the degree of gap penetration over the desired operating cycle to arrive at a desired design penetration for the jets.

8.11 Modifying Tube Shape In some embodiments, users preferably adjust tube shape to affect the pressure drop and flow across a contactor tube or contactor tube array or bank. They change tube shape to affect the vortex intensity and turbulence downstream of the tubes. Tube shape is also be used to influence the direction of flow and momentum of fluid flowing across tubes in some configurations. Flow induced differential ejection pressure across a contactor tube also causes bending forces and moments on the tubes.

In some embodiments, users selectively adjust the cross section shape of the contactor tubes to streamline a cylindrical tube 10 and orient perforated tube arrays to adjust these parameters, as needed or desired. . (See e.g., compare Figure 35, Figure 36 and Figure 37 with Figure 34.) By streamlining tube cross section, users preferably increase the tube's moment of inertia about the bending axis and increase its ability to resist the bending moments. Conversely, users sometimes adjust the cross section of the contactor 10 to form a more bluff or anti-streamlined configuration. (Compare e.g., the triangular contactor Figure 41 and streamlined cusped contactor Figure 42 with Figure 34.)

By forming a more bluff body shape on the downstream side of the tube, users increase the turbulence downstream of the tube, eventually forming two vortices downstream of the two outer edges. By such methods, users change parameters to improve present value of total system costs including capital, assembly and operating costs.

8.11.1 Circular Tubes

In some common configurations, users use generally circular tubes to form distribution tubes to deliver first fluid, such as, fuel or thermal diluent. A circular tube shape provides more turbulent vortex mixing than tube streamlined shapes. (See, e.g., Figure 34.)

8.11.2 Streamlined Non-circular Tubes

In some embodiments, users reduce the pressure drop across the contactor tube array while increasing the surface heat transfer coefficient by configuring the contactor fluid tubes and manifolds to a non-circular shape with the narrower cross section facing into the fluid flow. This reduces the parasitic pressure drop, reducing the pumping work to move the second fluid across the distributed contactor , but it reduces vortex mixing.

Elliptical or Oval Tubes: As shown in Figure 35, in some embodiments, a generally elliptical or oval tube 10 is used. Utilizing a generally simple process, a generally circular tube is pressed to flatten it from side to side to easily form the tube 10 into a generally elliptical or oval shape.

Symmetric Streamlined Aerodynamic Shape: As shown in Figure 36, in further embodiments, users further form the tube 10 into a more streamlined cross section using multiple forming rollers where the downstream tube portion is pressed narrower than the upstream portion. Such streamlined shapes generate some of the least vortex mixing.

Flattened Tubes: Gases have substantially higher volume than liquids for the same mass. The necessary liquid flow cross-sectional area through the distribution tube 10 is often much smaller than that of the gas flowing across the tube. Consequently, in still further embodiments as shown in Figure 37, users further flatten the tubes 10 to reduce the drag from the second fluid 904 flowing across the tube while retaining the stiffness to bending due to the cross-flow drag.

Dual Channel Internally Bonded Flattened Tubes: A flattened tube 10 will expand given sufficient internal pressure. In some embodiments, as shown in Figure 38, users internally bond the flattened tube walls near their middle to form a multi-passage compound contactor tube 220 while leaving room for liquid flow. Pressing an elliptical tube in the middle will form a dumbbell or figure "8" shape. Forming and bonding a flattened tube into this shape now generates two internal fluid ducts 222. In some embodiments, users continually bond a dumbbell shaped tube to form two fluid channels. In modified embodiments, users further flatten the ducts.

Single Channel Flattened Tube: In some embodiments as shown in Figure 39, by flattening one portion of the tube 10, users obtain a straightened figure "9" or "6" shaped tube. Users may internally bond the tube walls 30 by this forming pressure. In other embodiments users electro-weld the walls, or users internally coat the tube with a solder or braze and then heat bond the tube walls.

Asymmetric Aerodynamic Shape: In some embodiments as shown in Figure 40, users use aerodynamic wing shaped tubes 10 to preferentially redirect the fluid flow across the tube in

an efficient manner. By adjusting the degree of transverse "lift", users increase or decrease the degree of redirection.

8.11.3 Anti-streamlined Bluff Tubes

In some embodiments, users form the tubes into less streamlined shapes to increase the inherent turbulent mixing downstream of the tubes as needed or desired.

Transverse Elliptical Tubes: In some embodiments (compare, Figure 35), by orienting the long axis of an elliptical tube 10 normal (at 90°) to the flow axis of the second fluid, users increase the flow turbulence as well as the pressure drop across the perforated tubes. (i.e., by aligning the short axis of the ellipse with the second flow direction or the axis of the fluid duct 130.) By using tube shapes that are sufficiently bluff in the downstream direction, users form two vortex streams from either side of the anti-streamlined tube, thereby increasing mixing. E.g., as in a paddle or oar being pushed through a fluid with the bluff face in the direction of movement.

Hemispherical or Triangular Shapes: Users may use shapes that are somewhat streamlined upstream but bluff downstream in some embodiments to reduce pressure drop while creating flow separation with multiple vortices to improve mixing. E.g., as shown in Figure 41, a tube formed towards a semicircular or triangular cross-section. To increase drop shedding as the first fluid exits the distribution tube, users preferably position orifices near the widest transverse axis to provide about the greatest differential ejection pressure boost by the Bernoulli effect. For example, as shown in Figure 41, users position orifices near the downstream outside edge of triangular contractor tubes.

Cusped Bluff Tube: In some configurations, as shown in Figure 42 users preferably configure the downstream portion of the contactor tube 10 into one or more downstream facing cusps to form a cusped contactor tube 28. Using two cusps provides the advantage of assisting the downstream double vortex formed by the second fluid flowing past the tube that causes a lower pressure region which in turn results in a recirculating flow in the upstream direction towards the axis of the contactor tube 10.

8.12 Design Configuration As users narrow and streamline the distributed tubes, users reduce the drag of the second fluid flowing across the tube arrays. Conversely this increases the

capital cost of the tube arrays. Similarly as users increasing the tube-tube spacing H, users reduce the drag across the tube arrays. At the same time, users increase the length of the fluid duct and pressure vessel , as well as the pumping work to deliver the first fluid through micro-jets. These parameters will vary with the viscosity and thus the orifice size and temperature of both the injected first fluid and the transverse second fluid.

In some embodiments, users adjust the diameter, shape, spacing of tubes , the delivery velocity of fluids size of orifices, and differential delivery pressures to improve drop formation and/or micro-jet penetration and mixing of fluids while reducing the parasitic fluid pressure drop and fluid pumping losses, fluid filtration and associated costs.

8.13 Fluid Pressure Drop Ratios

With reference back to Figure 1, in many embodiments, users desire or need to control the ratio of the flow of the second fluid 904 that mixes with the flow of the first fluid 901 delivered through the contactor tubes10. This generally relates to the velocity ratio times the density ratio times the net cross-sectional flow area of the respective fluids 901, 904 normal to the fluid flow axis (or specific orifice areal density of orifice area to duct cross sectional area.) In many embodiments, the velocities in turn relate to the cumulative acceleration each fluid experiences from the pressure drop along the duct 130, for given fluids, pressures and temperatures etc.

For many embodiments, the corresponding primary control parameters are the pressure drop across the tube array relative to the differential ejection pressure drop across the contactor tube wall. The second fluid flow rate and pressure drop across the tube array is often held constant or varies relatively slowly in proportion to the pressure drop across the fluid duct 130 between the inlet 134 and outlet 136. Users generally primarily control the differential ejection pressure drop across the orifices of the respective distribution tubes to rapidly control the delivery of first fluid 901.

9 FORMING ARRAYS OF PERFORATED TUBES In some embodiments, users preferably form the perforated distribution tubes described above into various two or three dimensional arrays ranging from a circular (or elliptical) planar tube array 265 in a circular duct

144 as shown in Figure 50, to a cylindrical tube array 270 oriented axially in an annular duct 146 as shown in Figure 52, and to a rectangular tent tube array 268 in a rectangular duct 145 as shown in Figure 53. Such two or three dimensional arrays provide the benefit of more uniformly distributing and mixing the first fluid 901 flowing thru the tubes 10 and orifices 80 with the second fluid flow 904 within the fluid ducts. The second fluid flow 904 commonly flows across those tube arrays. E.g., users may spray water or fuel into air to uniformly mix them together within a duct. In some configurations, the second fluid flow 904 is delivered through such contactor arrays.

9.2 Tube Orientation to Duct Flow Tubes Perpendicular to the Duct or Flow Axis

With particular reference to Figure 50, in some embodiments, users preferably orient the perforated tubes 10 across and substantially perpendicular to (i.e., normal or at 90°) the fluid duct 144 and common flow axis of the second fluid 904. Figure 51 shows an expanded view of a section of the contactor 10 having orifices 80 from which are ejected micro-jets 903. In such an embodiment, the tubes 10 may be configured into a circular planar array 265 comprising a plurality of concentric circular tubes 10. E.g., Such a transverse circular planar array 265 generally provides a preferably or an improved distribution of droplets and greatest and most uniform mixing downstream of the contactor tubes 10 for a given tube length compared to tubes at other angles to the fluid duct 130. It provides fairly uniform distribution of vortices downstream of the contactors 10, and thus fairly uniform vortex mixing within the fluid 904 and transversely across the circular fluid duct 144 shown.

9.2.2 Tubes Parallel to the Duct or Flow Axis

As shown in Figure 52, in some embodiments, users provide an alternative tube orientation is where the perforated tubes 10 are oriented substantially parallel to or at a small angle to the axis of the second fluid 904 or the axis of the fluid duct 130. In this embodiment, users provide axially oriented contactor tubes 10 connected to one or more manifolds 240 or sub-manifolds 254, formed in an arc or desired curvilinear configuration, and positioned within an annular fluid duct 146 or duct section. This axial array orientation desirably provides greater

capability and flexibility in controlling the axial fluid distribution distribution of the first fluid 901 etc. delivered through the contactor tubes 10.

9.2.3 Tubes at an Angle to the Duct or Flow Axis

In some embodiments, users efficaciously orient the contactor tubes at some angle to the fluid duct and flow axis as needed or desired. This typically varies according to the two or three dimensional array configuration desired. For example, as shown in Figure 53, in one embodiment, the contactor tubes 10 are preferably configured at an longitudinal angle to the second flow path 4 of the second fluid 904 within a rectangular fluid duct 145. The contactors 10 are preferably connected to manifolds 240 oriented transversely to the duct 145.

Users preferably adjust the angle of the contactor tube 10 relative to the axis of the fluid duct 145 according to the relative degree of control over the axial fluid delivery distributions and profiles and the transverse fluid delivery distributions and profiles. These in turn affect the relative control over the transverse distributions and profiles compared to axial distributions and profiles of the respective fluid ratios.

9.3 Axial Profile Control

With continued reference to Figure 52, in such an embodiments, users may preferably also control the axial as well as transverse distributions and profiles of fluid delivery in the distributed contactor system 2 along the fluid duct 130 such as a rectangular duct 145.This is variously accomplished by distributing orifices 80 axially along the fluid duct 130 as well as transversely across the duct. This may include combinations of orienting orifices along the contactor tubes 10 and configuring tubes 10 across the duct 130. With reference to Figure 53, it may also comprise axially orienting the orifices 84, or radially orienting orifices 86 aligned with or with a component directed along the axis of the fluid duct 130 or second flow path in some configurations, such as the axial orientation of orifices 80 and contactor tubes 10.

9.4 Two Dimensional Tube Array Configurations

9.4.1 Elliptical/Circular/Spiral Arc Contactor Arrays

For elliptical or circular ducts, in some embodiments, users preferably form curvilinear sections 21 of perforated tubes into elliptical or circular arcs. For example, as shown Figure 54, users then form an array of such circular arcs 21 connected to at least one manifold, preferably

connected between two or more radial manifolds 240 (or secondary manifolds) to create an elliptical or circular planar array 265 with arc shaped flow passages. They similarly form the perforated curvilinear sections into one or more spiral shaped arcs. They then connect these spiral arcs to one or more manifolds or sub-manifolds to form a spiral contactor array (not shown.)

In other embodiments, users connect the contactor tubes to one radial manifold or sub-manifold . In modified embodiments, users further form a perforated tube into a single spiral and form a helical or pseudo circular contactor array. A spiral perforated tube is typically simple to form. As mentioned above, users preferably adjust the orifice diameter to compensate for the progressive pressure drop along the contactor tube from the manifold to the end of the contactor tube or to the center (e.g., outside to inside) resulting in more non-uniform micro-jet penetration or drop formation along the contactor tube.

9.4.2 Rectangular/Trapezoidal Contactor Arrays

With reference to Figure 55, in some embodiments, users form generally parallel arrays of perforated tubes 10 into rectangular planar arrays 266 for rectangular fluid ducts. To reduce pressure drops, users preferably run the perforated tubes 10 across the shorter dimension of the rectangular duct and preferably join the direct contactor perforated tubes 10 to manifolds 240 or sub-manifolds oriented about parallel to and generally along the long sides of the rectangular duct. Where sub-manifolds are used, they are in turn connected to manifolds 240. In other embodiments, users run the perforated tubes 10 across the longer dimension of the rectangle and connect them to one or more manifolds 240 running across the shorter dimension of the rectangular fluid duct 130. In other embodiments, users prepare four triangular arrays of direct contactor perforated tubes 10 preferably extending out from the center of the rectangle between radial manifolds 240 to form a four sided rectangular planar array (similar to a flattened quadrilateral pyramid).

9.4.3 Annular Contactor Arrays

As shown in Figure 56, for annular fluid ducts or sections of annular ducts, in some embodiments, users form perforated tubes 10 into an array of arcs running about parallel to the circumference of the annular duct. Users connect these perforated tubular arcs 10 to one or more

radial manifolds 240 or sub-manifolds to form an arc type annular planar array 267. In a modified embodiment shown in Figure 60, users may form the perforated tubes 10 into an annular array 267 of radial tubes. They connect them to one or more manifolds 240 or sub-manifolds 254 formed in arcs, to form a spoke type annular array (See, e.g., Figure 60).

9.5 Three Dimensional Spatial Arrays of Perforated Tubes With reference to Figure 54, Figure 55, and Figure 56, in some embodiments, users preferably take the two dimensional contactor arrays such as described herein, and extend them into three dimensional contactor arrays such as downstream opening concave arrays, downstream decreasing convex arrays or similar tent shaped forms as further described as follows.

9.5.1 Conical Array of Helical Wound Tubes

With reference to Figure 1, in some embodiments, users preferably wind the perforated tubes 10 into desired circular arcs (or forming a helix with a desired helical angle) about a conical or similar elliptical form. Using a fairly uniform tube to tube gap or spacing, this configuration efficiently fills the cross-sectional space of a elliptical or circular duct 130. At the same time, such configurations provide more room between adjacent tubes for axial flow of the second fluid and reduce the pressure drop across this tube array.

In a modified embodiment, shown in Figure 57, users may preferably provide at least one and more preferably two or more manifolds 240 or sub-manifolds 254 oriented about axially tangent to the conical surface, and are connected to tubes 10. Using multiple such manifold tubes 240 improves rigidity while reducing pressure drops along the perforated tubes 10.

9.5.2 Tent Shaped Tube Array

As shown in Figure 58 relative to Figure 55, for rectangular ducts, in some embodiments, users preferably take a rectangular array 266 of perforated tubes 10 and extend it to a three dimensional rectangular tent shaped array 268 of perforated tubes 10. Users preferably bond the perforated tubes 10 transverse to the flow between V shaped manifolds 240. In modified embodiments, users orient the perforated tubes 10 and manifolds 240 in the complementary directions. Here manifolds 240 are oriented about along one or more of the tent ridge and parallel

base edges. Users then bond the perforated tubes 10 between the base and ridge manifolds 240. This provides shorter tube lengths with greater control over axial fluid distributions and profiles.

9.5.3 Polygonal Pyramid:

In some embodiments users form a pyramid array of contactor tubes for rectangular ducts. Conceptually, users take the rectangular array formed from four triangular arrays of perforated tubes as described above and extend that array to three dimensional pyramid such as a trilateral pyramid or quadrilateral pyramid.

As with Figure 58, the perforated tubes are preferably bonded between radial manifolds oriented down the four extended edges of the pyramid. In a similar fashion users can form triangular pyramids from triangular arrays of perforated tubes connected to manifolds along the array edges. Similarly, users sometimes form hexagonal pyramids from triangular arrays of perforated tubes connected to manifolds along the array edges.

9.5.4 Annular Tent Tube Array

Annular ducts are often encountered in industry. E.g., between a compressor and a gas turbine. These annular ducts are often divided into multiple annular duct sections. Accordingly, as shown in Figure 59, in some embodiments, users preferably combine and adapt the annular perforated tube array concept (e.g., Figure 56) with the tent shaped perforated tube array e.g., Figure 58) to form annular arrays of contactor tubes. As shown in Figure 59, users may form a curvilinear tent shaped annular tent array 269 of perforated tubes 10 that generally conforms to a section of an annulus. Such an array 269 generally comprises a pair of annular arrays 267 as shown in Figure 59 oriented at an angle with respect to each other.

As shown in Figure 60, for gas turbine combustors, users preferably use a radial spoke configuration of direct contactors 10 connected to one or more arc manifolds 240 around the periphery of the annulus. Such a "3-D" annular tent array 269 provides the greatest control over the first fluid flow delivery distribution in the radial transverse direction. It also reduces the pressure drop across the annular array. This configuration further simplifies and shortens the transition pieces commonly used to transition from circular ducts to annular section ducts. This further reduces the flow redirection and inefficiencies typically encountered for such transitions.

In other configurations, users configure the direct contactors 10 into arcs and connect them to radial manifolds 240 or sub-manifolds 254.

9.5.5 Cylindrical Tube Array or "Can" array

In yet other embodiments, as shown in Figure 65, users form a cylindrical tube array 270, using perforated tubes 80 formed into circular arcs 21 connected to one or more axial manifolds 240 or sub-manifolds 254. Similarly they form axial direct contactors 80 to generally circular manifolds 240 or sub-manifolds 254. Such configurations provide a convenient means of mixing a first fluid uniformly with a second fluid flowing radially into or out of a circular duct.

9.5.6 "Top Hat" Tube Array

In modified embodiments, as shown in Figure 66, users adapt a cylindrical tube array 270, to form "top hat" or "can" shaped tube arrays 271 by adding a circular array 265 to the end of a cylindrical array. Users wrap perforated tubes 10 into a cylindrical or helical shape to form the sides and/or the top. These can be connected to manifolds 240 or sub-manifolds 254 as described herein in connection with one or more of the conical arrays 262, 264.

9.5.7 Bulbuous or "Dandelion" Tube Array

In some embodiments, as shown in Figure 67, users form contactor tubes 10 into a bulbuous shaped tube array 273 (or "Dandelion" or "tulip" shaped.) In some configurations, they connect the contactor tubes 10 to manifolds 240 or sub-manifolds preferably oriented generally along a great circle of the bulbuous array 273. The bulbuous array 273 is preferably oriented about the end of a fluid duct 130 generally configured as the "stem" of the array. This configuration preferably provides fluid mixing about a spherical or similarly bulbuous surface. The second fluid is delivered through the fluid duct 130 or "stem" into the inside of bulbuous array. The bulbuous array 273 is elongated in some modified configurations. Such configurations are useful for radiant exposed burners.

9.5.8 Extended Arrays Tube Arrays

For large fluid flows, in some embodiments, users preferably form larger extended arrays of perforated tubes by taking two or more of the two or three dimensional ("3-D") contactor array structures described herein and arranging them into extended arrays of such array structures as desired or needed. Accordingly, users take tubular arrays with circular, hexagonal, Cartesian or

similar footprints and replicate them in linear, circular, spatial arrays as desired or needed to fit into the corresponding fluid ducts or similar regions.

Similarly in various embodiments, users replicate sections of annular tube array to form part or all of an annular array. For circular or polygonal tube arrays are used that do not fill the desired fluid duct or spatial surface, users preferably provide blocking structures to fill the inter-array gaps and prevent fluid from flowing between the tube arrays without being desirably contacted by contactor tubes.

9.5.9 Array Opening Orientation

"Horn" Orientation: In some embodiments, as shown in Figure 69, users orient a downstream opening concave tube array such as a helically wound tube array 262 in the "horn" orientation with the apex or point upstream and "mouth" downstream relative to the fluid duct 130 or second fluid flow 904, when users need or desire the second fluid to flow across the tubes from outside/upstream of the tube array to the inside downstream of the array.

With Reference to Figure 1, such an embodiment may also comprise a series of circular curvilinear sections 21 connected by a pair of manifolds 240. With this orientation, the second fluid flow 904 entrains droplets or micro-jets of a first fluid 901 from the tube orifices 80 into the inside of the concave tube array 260 (or a similar tubular conical array) on its "downstream" or "interior" side.

"Funnel" Array Orientation: In other embodiments, as shown in Figure 68 users orient the conical array in a downstream decreasing convex array or "funnel" tube array configuration 264 with the apex or point downstream and the "mouth" upstream relative to the fluid duct 130 or second fluid flow 904. Similarly, as shown in Figure 70, the funnel tube array configuration may be formed by providing a plurality of transverse extending tubes 10 that are connected by a V–shaped manifold 240. This arrangement commonly causes the second fluid 904 to flow from upstream inside the downstream decreasing convex tubular array or "funnel" conical array 264 to the outside downstream of the convex array or "funnel" conical array 264 when users need or desire the droplets or micro-jets of the first fluid 901 to be entrained by the second fluid 904 to

outside the downstream side of the convex array or "funnel" conical array 264 as they exit the tube orifices 80.

9.6 Flow Direction Tube Offset A planar tube array, such as the circular array 265 shown in Figure 54, blocks part of the flow cross section, restricting the flow to the space between the tubes. This can cause a significant pressure drop in the fluid flow across it. e.g., of the 2nd fluid. To reduce this problem, in some embodiments, users preferably offset tubes along the flow velocity axis to increase the gap between tubes. This typically reduces the flow constriction and the pressure drop across the tubes. This generally generates substantial savings in parasitic pumping energy, resulting in savings of both capital and operating costs.

9.6.1 Offsetting adjacent tubes

For instance, in some configurations users offset adjacent contactor tubes 10 (See e.g., Figure 54) by about 122% of the tube spacing H to increase the gap G between the tubes 10 to about equal to the tube spacing W. E.g., using tubes of about 4 mm diameter on about 7 mm intervals, offsetting the tubes by about 8.5 mm will increase the gap G between tubes from about 3 mm to about 7 mm or about equal to the tube spacing. In this example, this offset increases the area between the tubes 10 to about equal to the unobstructed cross section of the flow.

In other embodiments, users similarly offset tubes 10 to increase the gaps between the tubes. While there is still significant drag across the tubes, offsetting adjacent tubes significantly reduces the flow constriction and consequent pressure drop. (See, e.g., Figure 57.)

9.6.2 Conical arrays

As shown in Figure 57 and described above, for circular flow ducts, some embodiments preferably use a conical or helical tube array rather than a planar circular array. With such an conical or helical array, the flow area between tubes can be increased to greater than the cross-sectional area of the total flow by sufficiently reducing the cone angle in the "horn" configuration.

Similarly, the flow area can be increased by increasing the cone angle to much greater than 180 degrees in the "funnel" configuration as shown in Figure 72. Here the upstream area of the array is larger than the downstream area.

9.6.3 Pleated array

At the other extreme, in some embodiments, users may increase gap area between tubes by offsetting alternating tubes upstream and downstream in a zig zag pattern to form a pleated array. For example, Figure 71 illustrates such a pleated array 284. In this embodiment, the inter-tube gap by forming tubes 10 into intermediate pleated arrays 284 with larger zigzags. Here they offset several tubes 10 in one axial direction along the fluid duct 130, then offset the next several tubes 10 in the other axial direction. The pleated array 284 comprises a pair of rectangular arrays 266 axially displaced and offset in the transverse direction by half the tube to tube spacing.

Similarly Figure 72 shows a larger pleated array composed of two tent shaped arrays 268. Each tent array 268 comprises a series of transverse extending tubes 10 that are connected by a V-shaped manifold 240. In this embodiment, the open end of the V-shaped manifold 240 is positioned upstream of the "ridge" or closed end of the tent array 268. In this manner, the tubes 10 form a pair of adjacent V-shaped tube banks. This arrangement significantly reduces the axial dimension of the fluid duct 130 and associated costs of the pressure vessel 170 while increasing the inter-tube gaps and reducing flow constrictions.

9.6.4 Compound arrays

In further embodiments, users combine and adapt these contactor array formations. For example, users use a conical tube array (See e.g., 68) in the center portion of the flow. They then take the pleated contactor array and form it into a circular pleated array to surround the conical tube array. (Compare Figure 71.) These examples of offsetting tubes generally apply fairly equally to forming circular arrays , rectangular arrays , annular arrays, or otherwise ordered arrays in respectively circular, rectangular and annular shaped ducts.

9.6.5 Tube spacing

In various embodiments, users space the tubes across the flow at intervals as needed or desired. With reference to Figure 27 and Figure 29, users preferably form an array of tubes 10 of diameter D, spaced at intervals H. This results in a gap G between the orifices where G = H - D. The tube spacing H and tube diameter D, and orifice area and differential ejection pressure are preferably adjusted so that the penetration distance of the micro-jets exiting the orifices 80 extend between about 1% and 200% of the tube to tube gap spacing G.

Where users perforate the tube 10 about a portion of the circumference of the tube, the tube spacing H is preferably equal to about the total width of the perforated area about the circumference. For example, the tube spacing may be nominally configured about 175% of the tube diameter D, preferably in the range of about 101% to 500% of the tube diameter D. Similarly, users may set the gap G between the tubes at about 1% to 400% of the tube diameter D. E.g., users may configure the tube spacing H to about 7 mm. This in a gap between tubes G of about 3 mm in the above example for tubes with diameter D of about 4 mm.

9.7 Drilling Orifices

In some embodiments, users preferably use laser drilling technology with a high Thickness to Diameter (T/D) drilling ratio to create numerous small orifices in tube walls 30. E.g., using technology with about 100:1 thickness/diameter drilling capability with 200 μm thick walls nominally enables formation of about 2 μm diameter orifices using suitable wavelength lasers. Such orifice drilling desirably combines a structural tube wall 30 with numerous fine orifices 80.With reference to Figure 2, Figure 3, Figure 4, Figure 5, and Figure 6, users further preferably form thin tube wall sections 32 through which they drill the orifices 80. This enables smaller holes for a given Thickness to Diameter drilling ratio, or conversely, using a less expansive technology with lower thickness/diameter ratio while achieving similarly sized orifices 80. E.g., using a carbon dioxide laser with T/D of about 10 to achieve 20 μm diameter orifices in a 200 μm thick wall.

With reference to Figure 43, Figure 44 and Figure 45, in other embodiments users use one or more of the compound perforated tube configurations 200 (which will be described in more detail below) with thicknesses of thin wall sections 32 of about 1% to 75% of the structural tube section 36, and preferably about 5% to 50% of the thickness of the structural wall 36. Using such measures, users readily form an array of fluid orifices 80 with orifice diameter from about 10% to 0.1% of the structural tube wall thickness (e.g., about 0.5% to 0.05% of the tube diameter). E.g., they may use more common laser drilling technologies with typically 10:1 Thickness/Diameter capability. Such combinations enable users to drill orifices ten times smaller with more conventional drilling equipment than with conventional relevant art. Preferably using drilling

technologies with higher drilling Thickness/diameter laser drilling capabilities of about 100:1 to 200:1 nominally increase this range of orifice sizes by an order of magnitude or more.

9.8 Drop Array Formation

Using such measures, users typically configure orifices to form micro-jets in a suitable array to desirably distribute droplets across the transverse flow. They similarly configure orifices along and/or about the tubes. In some embodiments, users direct orifices longitudinally relative to the cross flow. For example, configuring 10 μm orifices would nominally form droplets about 20 μm in diameter giving a specific surface area (surface area/volume) of about 2,500 $^{-1}$. Similarly a finer array of about 2 μm orifices, nominally forms about 4 μm droplets. Ignoring droplet coalescence, this would nominally create a specific surface area of about 125,000 $^{-1}$.

9.9 ManifoldsIn various embodiments described above, users preferably connect multiple distribution tubes to one or more manifolds. For example, as shown in Figure 50, Figure 52 and Figure 53 a manifold 240 connects a plurality of distribution tubes to each other. Relatively large manifolds 240 reduce the internal pressure drop and pumping losses of the first fluid flowing within the distribution tubes 10. They also provide some structural support for the distribution tubes 10 against the bending forces of the second fluid 904 flowing across the tubes 10 and manifolds 240 and for the pressure oscillations caused by vortices downstream of the tubes 10 and from resonant pressure oscillations. Various manifold configurations may be used such as shown in Figure 54 to Figure 60. E.g., aligning the manifolds along an edge of the duct or along a diagonal or radius of the array or other intersecting plane.

9.9.1 Streamlined or "Thin" Manifolds

By flattening the manifold(s) transverse to the fluid duct 130, in some embodiments, users form a "thin" or streamlined manifold. This reduces the drag or pressure drop for second fluid 904 flowing across the manifold, similarly to flattening the distribution tubes 10. Users also desirably increase the bending strength of the manifold 240 crosswise to the flow 904.

9.9.2 Sub-Manifold

In some configurations, as shown in Figure 60, users provide secondary manifolds or sub-manifolds 254 to further distribute the fluid from manifolds 240. The direct contactor tubes 10 are then preferably connected to the sub-manifolds 254.

9.9.3 Sub-Manifold Valves or Flow Modulators

With continued reference to Figure 60, to desirably control the flow of the first flow 901 through the contactor tubes 10, in some configurations users provide sub-manifold valves 233 and/or pressure flow modulators 370 to control the flow of fluid through manifolds 270 or sub-manifolds 254. They accordingly control the flow through the arrays of orifices 80 associated with those manifolds or sub-manifolds 254 such as those configured on the contactor tubes 10 connected to those manifolds or sub-manifolds 254.

By these measures, users preferably control the first fluid flow 901 relative to the second fluid flow 904 over one or more flow sub-regions as selected by the configuration of sub-manifold valves 233 allowing fluid to flow through select combinations of sub-manifolds. They similarly preferably control the flow through those selected sub-manifolds by controlling the pressure flow modulators 370.

9.9.4 Sub-manifold arrays

As will be apparent to one of skill in the art, in various configurations, users preferably connect contactor tubes to sub-manifolds and/or manifolds to achieve desired or needed groupings of orifices in a contactor array section relative to the flow of the second fluid through the contactor array section. They similarly configure the contactor array sections together with corresponding combinations of sub-manifold valves and/or pressure flow modulators. These arrays are variously configured in arithmetic, geometric arrays as desired to give the flexibility and turn-down ratio desired in the controls. Redundancy and/or degeneracy in these configurations is also provided in some configurations.

Arithmetic ratios: For example, users configure areas of contactor array sections in an arithmetic ratio of second fluid flow 904 through those sections. E.g., 1:1, 1:2, 1:3, 1:4, 1:5 etc. according to the respective turn-down ratios needed or desired.

Geometric ratios: Similarly, they configure contactor arrays in geometric ratios such as binary, 1:2:4, ternary 1:3:9, quaternary 1:4:16 etc.

Hybrid ratios: In other configurations, they configure arrays in combinations of such arrays or with degenerate combinations. E.g., such as 1:1:1, 1:1:2, 1:1:1:1, or 1:1:2:4.

9.9.5 Sub-manifold tube configurations

In configuring such contactor array sections, users preferably configure contactor tubes 10 in proportion to the desired contactor array sections areas. For example, preferably configure contactor tubes 10 in a radial or spoked configuration connected to sub-manifolds 254 configured along the inner and outer circumferences of the annular duct 146. They similarly configure tubes to sub-manifolds S1, S2 and S3 respectively in a repeated pattern: #1, #2, #1, #3, #1, #2, #1. (See, e.g., Figure 60.)

This configuration provides four tubes #1 to sub-manifold S1, interspersed with two tubes #2 connected to sub-manifold S2, interspersed with one tube#3 connected to sub-manifold S3. Where each of these radial contactor tubes 10 are of similar size and length, with about an equal number of orifices, users obtain orifices in the proportion of about 4: 2: 1. These deliver flows of first fluid 901 in proportion to flows of second fluid 904 by array sections.

9.9.6 Varying internal manifold cross-sectional area

In some embodiments, manifolds 240 are varied in cross-sectional area with distance to compensate for the fluid delivered to the perforated tubes 10. The manifold's internal cross-sectional area preferably varies proportional to the remaining first fluid flow rate as the distance along the manifold. E.g., as distance along a radius, an edge, or similar parameter.

9.10 Contactor Tube and Fluid Delivery Profiles To provide desired flexibility on fluid delivery, users preferably control transverse or axial distributions and profiles of one or more parameters along the tube contactors or contactor arrays in some embodiments.

9.10.1 Orifice Size & Jet Penetration Distance

In some configurations, users adjust the orifice size and differential ejection pressure across the tube wall to achieve desired micro-jet penetration distances. For example, as shown in Figure 60, where radial contactor tubes 10 are configured across an annular duct 146, users increase the orifice size with increasing radial position to accommodate the increasing tube to tube gap.

9.10.2 Orifice spacing profile

In some configurations users preferably configure the transverse distribution of the spacing of the orifices 80 along one or both transverse directions and/or axial directions, to

provide a spatial orifice density to achieve a desired orifice area distribution and profile along that transverse or axial direction.

9.10.3 Spatial area density profile

In some embodiments, users combine one or more features of changing orifice size, orifice spacing, and tube spacing to achieve a desired spatial area density of orifices 80 delivering the first fluid 901 along one or more directions transverse to the fluid duct 130 and the second fluid flow direction 904.

9.10.4 Spatial fluid delivery profiles

Users combine the prescribed spatial area density distributions and profiles with controlling the differential fluid pressure distribution across the tube walls to provide a desired first fluid delivery distribution in some configurations. For example, to accommodate varying transverse profiles of axial velocity in the second fluid 904, users combine the profiles of orifice size, orifice spacing, tube gap and differential ejection pressure to achieve a desired first fluid delivery distribution relative to the transverse flow distributions of the second fluid 904 and one or more of the first and second transverse directions and the axial direction.

9.11 **Tube Ribs or Stiffening Supports**Flow of the second fluid 904 over the perforated distribution tubes 10 causes turbulence, pressure drops and a flow drag force in the direction of the second flow or fluid duct 130. Contactor tubes 10 oriented transverse to the flow of the second fluid 904 are also subject to bending forces by the flow drag. Accordingly, as shown in Figure 1, in some embodiments, users preferably support these distribution tubes 10 by attaching one or more supporting stiffeners or external tube supports 37 to the contactor tubes 10.

9.11.1 Structural supports

In some embodiments, as shown in Figure 68, users attach the tube support or external stiffeners 37 to at least one upstream structural support 72 attached to the fluid duct so as to support the drag forces on the tube array which are transferred to the tube supports 37. In some configurations, these tube supports 37 are connected to a manifold 240, central manifold header or other structural support that can sustain the cumulative drag. Users preferably use a multiplicity of tube supports 37 to provide transverse supports and counter the turbulence induced force moments and array vibration or oscillation.

9.12 Tube Surface

9.12.2 Tube Surface Energy

With reference back to Figure 13, the difference in surface energy between the first fluid 901 being expelled from the contactor tube 10 and the outer surface of the tube 80 affects whether the fluid will "wet" the surface of the tube 80 or be repelled from it. When a second fluid 904 is present flowing across that surface, this difference in surface energy should also be compared with the difference in surface energy between that fluid and the tube surface. To assist droplet formation and to prevent the first fluid from wetting the exterior of the tube, in some embodiments, users preferably treat the tube surface to change its surface energy to repel the first fluid at least about and downstream of the orifices. E.g., providing a "hydrophobic" surface when delivering water through the orifices, or correspondingly "oleophobic" surface (commonly also "hydrophilic" surface) when distributing diesel fuel or similar "oleophilic" hydrocarbon fuel.

9.12.3 Tube Surface Roughness

In some embodiments, users preferably create very small scale roughness or texture on the exterior of the tube 10 about and downstream of the orifices 80. This helps repel drops and prevent a liquid 901 from wetting the tube outer surface and so assist in drop formation and avoid "wetting" or dribbling" down the outer surface of the contactor tube 10.

10 FORMING SMALLER ORIFICES

10.3 Smaller Orifices

As shown in Figure 2 to Figure 6, in some configurations, users preferably form thin sections 32 in tube walls 30 to assist in making smaller orifices than are readily formed in thicker walls.

10.3.1 Laser drilling for smaller orifices

Various techniques may be used to create the small orifices describe above. For example, users may use several different technologies to create orifices, such as laser drilling, photo-lithographic etching, x-ray lithographic etching, among others. Users preferably select the laser power, frequency and optics according to the orifice diameter and uniformity required. Common CO_2 lasers can achieve about 20 μm diameter orifices. To achieve smaller diameters, users sometimes utilize lasers with smaller wavelengths (higher frequencies.) Eximer lasers can drill orifices of about 1 μm to about 2 μm in diameter with Thickness to Diameter ratios (t/d) of up to

100 or even 200. E.g., in ink jet orifice arrays. Ultraviolet lasers can achieve sub micrometer orifice sizes.

Users may also utilize other drilling methods. For example, friction drilling, mechanical punching, electro drilling. Users typically use these for larger orifices such as forming orifices in manifold ducts where tubes are connected.

10.3.2 Tube Wall Thickness vs Tube Diameter

Table 3 shows an exemplary embodiment of the variation in the thickness of the tube wall 30 as a function of tube wall thickness to diameter ratios for a range of tube diameters from 1 mm to 16 mm.

Table 3 Tube Wall Thickness µm versus Tube Diameter for various Tube Wall Thickness/Tube Diameters

Tube Wall Thickness/ Diameter	Tube Outer Diameter mm									
	16	12	10	8	6	5	4	3	2	1
4	4000	3000	2500	2000	1500	1250	1000	750	500	*250*
6	2667	2000	1667	1333	1000	833	667	500	*333*	*167*
8	2000	1500	1250	1000	750	625	500	375	*250*	*125*
10	1600	1200	1000	800	600	500	400	*300*	*200*	*100*
12	1667	1000	933	750	500	418	*333*	*250*	*166*	*83*

10.3.3 Wall Thickness to Orifice Diameter Ratio

Laser drilling can typically achieve a given Wall Thickness ("depth" or orifice "length") to Orifice Diameter ratios (t/d). E.g., Common laser drilling technology can achieve Wall Thickness/Orifice Diameter ratios of 10:1. Some technologies can achieve Wall Thickness/Orifice Diameter ratios of 100:1 to 200:1 with Eximer lasers, depending on wavelength. With laser drilling, the orifice size is thus limited to the thickness of the sheet drilled, divided by the Wall Thickness/Orifice Diameter (t/d) ratio for a given wavelength. e.g., about 20 μm to 1 μm diameter holes in a 200 μm wall for Wall Thickness/Orifice Diameter ratios of 10:1 to 200:1.

Table 4 shows embodiments of the consequent orifice diameters for various thicknesses of the tube wall 30 as a function of wall thickness to orifice diameter ratio of the drilling technology used.

Table 4 Orifice Diameter μm versus Wall Thickness μm
for various Wall Thickness/Orifice Diameter Limits

Thickness/ Diameter	Wall or Sheet Thickness micrometers (μm)									
	1000	500	200	100	50	20	10	5	2	1
2	500	250	100	50	25	10	5	2.5	1	0.5
5	200	100	40	20	10	4	2	1	0.4	*0.2*
10	100	50	20	10	5	2	1	0.5	*0.2*	*0.1*
20	50	25	10	5	2.5	1	0.5	*0.25*	*0.1*	*0.1*
50	20	10	4	2	1	0.4	*0.2*	*0.1*	*0.04*	*0*
100	10	5	2	1	0.5	*0.2*	*0.1*	*0.1*	*0*	*0*

10.3.4 Many Orifices

As mentioned above, some embodiments of the invention form direct contactors 10 using a few to tens to hundreds of orifices 80 per mm of tube length. E.g., selecting about 80 orifices per mm typically of 50 μm in diameter, with 3 meters of thin walled tube would provide about 3,000 orifices. Similarly, by making about 20 μm orifices 80 every 60 μm along a thin walled tube, users create about 17 orifices/mm tube length. By wrapping about 3 meters (m) of such thin walled perforated tubing into a direct contactor perforated tube array 260, users provide up to about 50,000 orifices distributed across the flow. E.g as shown in Figure 1, in a downstream opening conical or "horn" distributed fluid contactor 260. Similarly, by reducing orifice size to about 2 μm spaced about every 6 μm axially along a perforated tube in about 200 axial rows circumferentially about that tube, users nominally achieve about 33,000 orifices/mm tube length. Using about 3 m of such conical distributed fluid contactor, users would advantageously provide about 100 million orifices distributed across the flow.

These methods provide far greater number of nozzles than conventional systems which provide just a few nozzles with one or a few orifices per nozzle. E.g., a large bore Diesel engine may use three nozzles each with six orifices, forming a total of 18 orifices.

10.4 Thin Wall Perforated Tubes Conventional Diesel injectors may use 10 micrometer (μm) to 60 micrometer (μm) diameter orifices with high pressure heavy walled tubing. By preferably using many smaller orifices users significantly reduce the injection pressure and pumping work to create numerous small drops or droplets while significantly improving the spatial control over transverse distribution of flows and flow rate profiles in the first and second transverse and axial directions. Modified configurations could also use many conventional nozzles or injectors distributed across the flow, though at higher expense and without as precise control over spacing.

10.4.1 Thin Walled Tubes

Thin-walled tubes with diameter to wall thickness ratios (D/t) of 8 to 10 are available (e.g., with 760 μm or 0.030" OD, and 500 μm or 0.020" ID). Users nominally consider "thin wall tubes" as having wall thicknesses of 1,000 micrometer (μm) to 200 μm.

Users preferably use such thin wall tubing to make 100 micrometer (μm(to 20 μm diameter orifices (0.004" to 0.000,8" diameter orifices) directly in the thin tube wall 30 using an orifice forming technology such as laser drilling. Users preferably use technologies which can form orifices with a 10:1 Wall Thickness/Orifice Diameter (t/d) ratio and more preferably with a thickness/diameter ratio (t/d) of 100:1 to 200:1. With such orifices 80, users advantageously form simple drops with diameters in the range from about 200 (μm) to 40 μm with low differential positive pressures and flows. With such thin walls, users can further reduce the orifice sizes down to a range of about 10 micrometer (μm) to 2 μm by using laser drilling technology capable of Wall Thickness to Orifice Diameter (t/d) ratios of 100:1 etc.

Of course, as the skilled artisan will appreciate, other suitable nominal thicknesses for the thin wall tubes may be efficaciously utilized, as needed or desired, giving due consideration to the goals of achieving one or more of the benefits and advantages as taught or suggested herein.

10.4.2 Ultra-Thin Wall Perforated Tubes

For still smaller orifices, in some embodiments such as with low differential ejection pressures, users select thinner walled tubing or use orifice forming technologies capable of higher Thickness/Diameter (t/d) ratios. Ultra-thin walled tubes are commonly available with wall thicknesses from about 200 micrometer (μm) down to about 125 μm (about 0.008" to 0.005") or even to about 75 μm (about 0.003"). With such ultra-thin walled tubing, users readily form orifices with diameters down to about 20 micrometer (μm) to 8 μm using laser hole drilling technology capable of Thickness / Diameter ratios of 10:1. With 100:1 laser drilling technology using short wavelength (high frequency) lasers, users could potentially form orifices of 2 micrometer (μm) to 0.8 μm in diameter with such ultra-thin wall tubing.

10.5 Thinning Walls for Smaller Orifices in Thin Walled Tubes The size of holes formed in tubing is nominally limited by the thickness of the tubing and the Length/Diameter capabilities of the hole forming method. As shown in Figure 3 and mentioned above, in modified embodiments, users thin the tube wall 30 to form a thin tube wall section 32 to assist in forming smaller diameter holes. E.g., Tube walls 30 are machined, or ground thinner, or thinned by electrochemical machining to form thin tube wall sections 32. In other embodiments, as shown in Figure 3, a portion from about 5% to about 95% of the tube wall 30 is removed to form a thin tube wall section 32 using suitable thinning methods. (E.g., See Figure 3.)

The final thickness is preferably refined by precision surface grinding as desired or needed. For example, with precision grinding to a tolerance of about 2.5 μm (0.0001"), users nominally machine a tube of about 4 mm diameter with about 200 μm thick walls and then surface grind the tube wall 30 to form a thin tube wall 32 with a thickness of about 20 μm to about 30 μm.

10.5.1 Grind arcs on tubing

To form thinner walls, in some embodiments as shown in Figure 4, users grind a curved surface or arc onto the tube wall 30 to create a thin wall section 32 aligned axially along the outer surface of the tubing. The wall thickness at the thinnest sections could be coarsely machined and then ground down to a wall thickness of a given a multiple of the grinding precision tolerance.

E.g., grinding the wall thickness to about a 10 fold multiple of a grinding precision of about 2.5 μm would nominally permit grinding down to nominally 25 μm thick walls.

CNC Industries of Fort Wayne IN USA, and Alpha Technologie company of Thyez France, are two companies for example specializing in precision surface grinding. They claim to nominally hold the surface tolerance to 2.5 micrometers (0.0001") with precision grinding. This is about 10% of the desired final wall thickness.

10.5.2 Forming Thin Sheet into Thin Walled Tubing

To further improve on the uniformity of forming thin walled tubing, in another embodiment as shown in Figure 34, users preferably take thin sheet with substantially uniform thickness, bend and form it into a thin wall tube 10. The sheet edges are then bonded together to complete the tube. This method creates the tube wall 30 with much greater wall uniformity than conventional drawing or grinding etc. Consequently, the orifices created will have much more uniform diameters for drilling technologies using a similar thickness to diameter ratio (t/d).

10.5.3 Drilling Holes in Thin Walls

In configurations using an ultra thin wall thickness of about 25 micrometers, users can drill holes of about 2.5 μm to 0.25 μm, using a drilling technology with a thickness/diameter ratios of about 10:1 to 100:1. Thus, the hole diameter achievable is of the order of the precision of the thickness of the thin wall 32. e.g., forming foils or surface grinding tolerance. Users may drill multiple holes 80 transversely around the perimeter of the tube 10 in this thin wall section 32. Users may then replicate such linear arrays along the length of the tube, or vice versa.

10.5.4 Multiple arcs or flats around tubing

As shown in Figure 3 and Figure 4, this methodology may then be extended to form thin wall sections 32 (multiple arcs or flats) in the tube wall 30 around the contactor tube 10. E.g., two thin wall sections 32 on either side of the tube 10. The number of arcs or flats can be extended to three, four, five or more sections around the tube. e.g., in hexagonal arcs or flats.

10.6 Micro-Orifices in Compound Thin Walled Perforated Tubes With reference now to Figure 43, to distribute smaller orifice , in some embodiments, users form compound perforated tubes 200 with thinner walls 33 by bonding perforated thin tube side walls 32 (e.g., formed strips or foils) to heavier formed tube stiffeners 36 (e.g., structural supports.) In some

embodiments users form smaller orifices 80 using technologies (such as Laser drilling) with higher Thickness/Diameter ratios and/or smaller radiation wavelengths (higher frequency).

Practical ultra-thin wall tube systems may require structural support to withstand the bending forces of the external second fluid flow across the tube as well as to handle forces due to gravity and vibration. To support these bending forces, in some embodiments users take a thicker upstream tube stiffener portion 36 formed from strips thick enough to provide structural support. Users make the small orifices through one or more thin perforated strips and form them into the downstream portion of the tube 36.

Users preferably form an ultra-thin walled compound perforated tube by bonding the downstream thin tube wall 33 to the upstream structural tube portion 36. E.g users bond thin strips 32, of about 500 micrometer (μm) to 50 μm thick, onto thicker tube structural support wall sections 36, either within or without the upstream support. With this construction method, users advantageously create compound contactor tubes 10 with effectively larger tube diameter/wall thickness ratio.

10.6.1Forming Small Orifices in Thin Sheets or Foils

With a range of Thickness/Diameter orifice forming technologies and thin sheet or foil thicknesses available, users variously achieve orifice diameters of about 25 micrometer (μm) down to sub-micron sizes for a range of sheet thickness from about 1000 micrometer (μm) to 1 μm. (Smaller orifices can be formed with deep ultra-violet, electron or x-ray forming technologies as these technologies progress.) Assuming pendant drops are formed with sizes twice the orifice diameter, users nominally form uniform drops from about 50 micrometer (μm) to 0.5 μm in diameter from an array of orifices of substantially uniform size.

10.6.2 Compound Foil-Walled Perforated Tubes

In further embodiments, users form ultra-thin walled compound tubes using even thinner sheets or "foil" to create thin walls 32 with still smaller orifices. e.g., walls less than about 50 μm thick. Stainless steel structural foils are available at least in about 30 micrometer (μm), 25 μm, and 20 μm thin sheets. E.g., Metal Foils, LLC provides stainless steel foils from 250 micrometer (μm) down to 25 μm (0.010" down to 0.001"). Emitec Inc. of Auburn Hills, Michigan, and

Lohmar in Germany, manufacturer heat exchangers using foils of such thicknesses which they purchase from at least three reliable manufacturers.

Given the thinnest acceptable thin wall (e.g., metal foil thickness), users preferably divide by the Wall Thickness / Orifice Diameter ratio of the drilling technology used to arrive at the orifice diameter. (e.g., divide wall thickness by 10 for common laser drilling technologies.) To achieve smaller orifices, users can select shorter wavelength (higher frequency) lasers and/or use lasers capable of higher Wall Thickness / Orifice Diameter ratios as needed or desired. (Some companies claim Wall Thickness / Orifice Diameter ratios of 100 or higher for eximer laser drilling etc.) Thus, users can laser drill about 2 μm to 0.2 μm diameter orifices through 20 μm thick stainless steel foil. (Conversely, given a desired orifice diameter and the Wall Thickness / Orifice Diameter limit of a drilling technique, users can calculate the desired thickness of the thin tube wall 32 e.g., sheet or foil.)

In modified configurations users utilize even thinner foils. E.g., ACF Metals of Tucson Arizona makes ultra-thin metal foils with thicknesses of about 5 micrometers (µm) down to about 1 nanometer (nm).

10.7 Two Section Compound Perforated Tube Cut Structural Strip

With reference back to Figure 43, a modified embodiment, users form a thin wall 32 by cutting a thin stainless steel sheet and cut a structural strip to a width about equal to the circumference of the upstream portion of an elliptical support tube section. I.e. the sheet is cut to a width of about $\pi D/2$. As an example, to create a half tube about 4 mm in outer diameter, a stainless steel sheet of about 0.2 to 1.0 mm thick is selected depending on the bending strength or stiffness required. This is then cut to a width of about 6.3 mm. This strip is then formed into the desired upstream streamlined shape.

10.7.2 Thin Wall Strip

In other embodiments, the downstream thin wall portion 32 is formed by cutting a thin strip 32 from thin sheet material or foil. For example, users select the stainless steel foil with thin commercially available thickness, preferably about the desired diameter of the orifices times the length/diameter ratio of the hole forming method. E.g., about 20 to 30 μm (about 0.02 mm to

about 0.03 mm) thick to prepare small holes about 2 μm to 3 μm in diameter, using a laser capable of drilling holes with a 10:1 length/diameter ratio.

10.7.3 Thin foil downstream perforated wall section

Wrapped downstream portion: In still other embodiments, the ultra-thin sheet is cut into a strip about equal to the circumference of the desired tube. This is formed into the desired shape and wrapped around the upper structural tube portion to form the thin tube wall.

Part downstream portion: As shown in Figure 43, in some embodiments, users form a thin tube wall 32 from a strip of stainless steel foil about equal to the circumference of the portion of the desired tube downstream of an upstream structural tube support 36, plus an amount to overlap and bond to the upstream portion. For example, the downstream portion may be about 7.5 mm to 8.5 mm wide, with about 0.5 mm to about 1 mm overlap on each side. This results in a strip thin tube wall 32 about 8.5 mm to 10.5 mm wide.

10.7.4 Indented attachment edges

In some modified embodiments, as shown in Figure 43 and Figure 44, users press or grind a thin indent 256 a little greater than the thickness of the perforated thin wall 32 (foil) on each outer edge of the structural tube strip 36. e.g., about 25 to 35 micrometers deep. Users preferably form the width of the indent 256 about equal to or a little greater than the desired attachment width of the thin wall 32 (foil). E.g., about 0.6 mm to 1.1 mm inward on both outer edges of the structural strip. This provides the benefit of reducing turbulence at the joint between lower to upper tube portions. Various companies claim capability to grind with a precision of about 2.5 μm (0.000,1"). This is about 10% of the desired indent depth.

10.8 Perforate Thin Strip or Foil In various embodiments, the thin wall 32 (strip or foil strip) is perforated with a pattern of fine holes 80 in one or two dimensional arrays or patterns as desired.

Laser drilling: The preferred method of forming orifices 80 is to use lasers to drill fine orifices proportional to the thickness of the material limited by the length/diameter capability of the laser. E.g., the Department of Defense sought a Small Business Innovative Research (SBIR) project #AF02-003 to drill large numbers of 170 μm holes with very high precision. High power

lasers evaporate material rapidly, leaving clean uniform holes. Shorter wavelength higher frequency lasers may be used to drill smaller holes. E.g., Ultra-violet lasers can prepare holes down to micrometer or sub-micrometer capability.

Mechanical punch: In other embodiments, users may form linear or spatial arrays of micro-punches to press holes 80 through thin foils.

Electro drill: In further embodiments, users may form holes 80 using an electrode type removal process.

Resist Etch: In some embodiments, users may form holes 80 using a photo-etch method with a resist, similar to methods of forming circuit boards.

Form Longitudinal perforated array: In various embodiments, users preferably form an array of orifices 80 longitudinally along the thin wall 32. In other embodiments, users may form two parallel arrays, leaving a solid section in the middle and on either edge. The width of the array is preferably about 1.0 to about 1.5 times the diameter of the tube.

As an example, in some embodiments, users form two parallel arrays about 3.5 mm wide on either side of a solid center band about 1.5 mm wide, leaving a solid strip on either edge of about 0.75 mm wide to which to bond the foil to the tube. This results in perforating about 7 mm of a foil strip of about 10 mm width.

10.8.1 Bond perforated downstream portion to structural portion

In various embodiments, users preferably wrap the lower perforated tube portion 32 around the upper structural portion 36 as shown in Figure 43 and Figure 44. The upper edges of the downstream portion are bonded to the upper portion.

In other embodiments, users form the downstream portion 32 and position it to overlap the upper structural portion 36. Where indents 256 are formed, the edges of the lower thin side wall section 32 are preferably positioned into the indents 256 in the upper portion.

Both edges of the perforated downstream half tube are bonded to the supporting half tube support 36. E.g., by induction welding, friction welding, brazing, soldering or gluing according to the temperature and strength required.

10.9 Supported Compound Foil-Wall Perforated Tubes

Thin walls 32 limit

the differential ejection pressure that a perforated wall can support. The thinner the tube wall 32 (or foil), the lower the differential ejection pressure or span that the tube can typically tolerate.

As shown in Figure 44, in some embodiments, to accommodate thinner walls or foils, users support the thin wall 32 with a heavier structural support 202 having large openings. (For example, users form large orifices 80 in a suitable structural strip to form the tube structural support 202). Users further form smaller orifices 80 in thin tube wall 32 to form a thin perforated tube wall. They then line the perforated thin wall 32 about the inside of the perforated tube support strip 202 (e.g., a perforated tube 10 with large orifices.) The large orifices 80 in the structural support 202 reduce the span across which the thin wall 32 (or foil) needs to support the differential pressure. The structural support 202 also supports the foil against the drag from the cross-flow and against the differential fluid pressure.

In alternative embodiments, users form thin perforated wall or foil around the large holed structural support 202. They then bond the thin wall 32 to the supporting large holed perforated tube 202.

10.10 Centrally Stiffened Compound Perforated Tube

Thin perforated foil (e.g., about 20 micrometer (μm) to about 30 μm thick) is relatively weak and deformable. As shown in Figure 45, in some embodiments, users preferably attach a perforated thin wall 32 (e.g., foil) to a structural support section 202 comprising one or two axial structural tube support sections 36 to support and stiffen it. E.g., bond about 200 micrometer (μm) tube side wall 32 (foil) to about 1 mm (1,000 μm) thicker axial support section 36. In modified embodiments, users form a stiffening tube strip 36 for the downstream portion of the compound perforated tube. E.g., cut a strip about 1.5 mm wide by about 0.2 mm to 1.0 mm thick.

10.10.1 Attach central stiffening strip

With reference to Figure 48, users may attach or bond one stiffening strip 36 down the middle of the perforated thin wall 32 (foil) on the solid axial section of the foil between the two perforated thin wall sections 32. E.g., on about 1.5 mm section. Users variously bond the components by induction welding, electrical spot welding, capacitance discharge welding, friction welding, brazing, soldering or gluing according to the temperature and strength required.

10.10.2 Form support tube into upstream streamlined shape

As shown in Figure 43 to Figure 44, the structural support strip 36 may be formed into an upstream streamlined shape. This shape approximates a half ellipse with the open side being the shorter axis. For instance, in some moderate sized embodiments, the outer dimension may be configured from about 0.5 mm to 50 mm, and more preferably from 2 mm to 10 mm wide. Of course, in other embodiments, the structural support strip may have a different shape.

10.10.3 Form stiffened perforated foil into downstream streamlined shape

In other embodiments, users form the stiffened perforated foil wall strip 33 into a desired downstream streamlined shape as shown in Figure 43 to Figure 45. This will approximate a narrowed half ellipse with the open side being the shorter axis. For example, the outer dimension may be about 2 mm to 10 mm wide resulting in a circumference of about 3 mm to 15 mm.

10.10.4 Fit perforated foil tube to structural support half tube

To assemble the embodiment illustrated in Figure 43, users may spread the stiffened perforated lower half thin tube wall 33 and fit it over the upper half support tube stiffener 36. In some embodiments users align the edges of the perforated foil into the indent 256 along one edge of the formed structural strip 36. In the embodiment of Figure 47, users preferably wrap the perforated thin wall 32 (strip) over and around the upstream structural part tube 36.

10.10.5 Bond foil to tube

With continued reference to Figure 43, users preferably bond both edges of the stiffened perforated foil half tube 33 to the supporting half tube 36. E.g., by induction welding, friction welding, brazing, soldering or gluing according to the temperature and strength required.

10.11 Transversely Stiffened Compound Tube In some embodiments, users form a compound perforated tube 200 from a thin wall section 32 over structural support 202 formed from components. E.g., they form the support 202 using periodic curvilinear circumferential tube structural supports 38 between the upstream tube support 36 and the downstream stiffener 36 to which the thin perforated walls 32 are attached. Large openings in the structural support 202 may be variously formed as circles, slots, rectangular holes and other openings.

10.11.1 Assemble skeleton tube from components

As shown in Figure 45, the compound tube may include periodic circumferential stiffener sections 38 between the preformed upstream tube support 36 and the downstream stiffener 36 to form a structural tube support 202.

10.11.2 Attach perforated foil(s)

As shown in Figure 45, the perforated thin wall section 32 (foil) are preferably attached to the inside of the "skeleton" tube or formed structural support 202. e.g., comprising axial tube stiffener(s) 36 and circumferential tube structural sections 38.

10.12 Forming Curved Perforated Tubes When tubes are bent into a curve, there is a danger of flattening or crinkling the tube side walls 33. Users may use relevant art bending methods, such as filling the tube with a liquid and then cool the liquid to a solid. E.g., with beeswax, a hydrocarbon with a high melting point, or with a fusible metal (preferably gallium, historically lead). After the tube is bent into shape, the tube is heated and evacuated to remove the forming solid.

10.12.1 Forming Curved Compound Tube Sections

It should be appreciated that the compound tubes described above may be formed into arcs, helices or other non-linear curves and formed into the various arrays described above (See e.g., Figure 54 to Figure 67.) In such configurations, users form the upstream tube support section 36 and the downstream tube support section 36 to the desired curvilinear shape.

10.12.2 Assembling Curved Tube Sections

The upstream tube portion 36, and downstream tube portion 36 are then assembled and bonded together into or near the desired final shape. This method significantly reduces the likelihood that the thin perforated walls 32 will tear or wrinkle compared to the damage that could happen if linear compound tubes 200 are assembled and then formed into an arc, helix or other non-linear curve.

10.13 Skeleton Compound Tube Formation

In some embodiments, as shown in Figure 45, users provide one or more circumferential tube structural sections 38 circumferentially from the upstream structural tube portion 36 around (or within) the perforated tube wall section 33 to support it.

10.13.1 Remove gaps between stiffener arcs

With continued reference to Figure 45, in some embodiments users form the structural tube support 202 by machining and grinding away tube side sections, leaving circumferential stiffener sections 38 in place between the upper and lower tubular stiffener sections 36. Then users assemble the compound tube 200 by attaching the perforated thin walls 32 (or "foils") to the sides or around the structural tube sections 36 and 38 as described herein.

10.13.2 Herringbone compound perforated tube assembly

In modified embodiments users attach circumferential tube support sections 38 approximately perpendicular to the central tube stiffener 36 on the perforated thin tube wall 32 (sheet or foil) like a covered herringbone. The stiffened perforated thin wall 32 is then formed into the desired cross-sectional shape (e.g., streamlined or bluff). This downstream stiffened perforated wall section is then bonded to the upper support tube section 36.

10.14 Compound Wire Tubes

As shown in Figure 47, in some embodiments, users preferably form compound perforated tubes 200 by wrapping a thin strip 201 around one or more structural tube support(s) 36 and using a bond 39 to those supports 202. Axial structural components 36 such as wires are readily used to form such structural supports 36. The curved shape of the wires preferably provides the streamlining form upstream and downstream. The wires further provide strength and rigidity to support the perforated tubes against drag and turbulence within the second fluid. As shown in Figure 48, in a modified embodiment, both wires may be the same to form an oval or elliptically shaped compound contactor 200.

10.14.1 Modified wire sizes and shape

As shown in Figures 47 and 46, in some embodiments, users preferably select an larger diameter wire for the upstream axial structural 36 and smaller diameter wire as downstream axial structural support 36 downstream. Where even more streamlined versions are desired, the thin strip preferably extends beyond the downstream wire to a narrower trailing edge.

Conversely, such configurations may be used to increase turbulence by orienting the bluff side of the contactor 10 or 200 towards the flow (i.e. the longer axis perpendicular to the flow.)

As shown in Figure 48 and Figure 46, users form the support wires 36 into more semicircular shapes in modified embodiments. The curved portions of the structural supports 36 are preferably configured outward and the flattened portions inward with respect to the tube.

10.14.2 Thin strip assembly

Figure 47 illustrates a modified embodiment, in which users warp a thin strip 32 around one support wire 36 and abutted around a second support wire 36. The thin strip 32 is preferably bonded to at least one of the wires 36.

In another embodiment illustrated in Figure 49, two thin strips 32 are laid up on either side of two wires 36 and preferably bonded to both wires. In a preferred modification as shown in Figure 47, the thin strips 32 wrap around the larger upstream wire 36 and preferably butt together. These thin strips 32 extend beyond a smaller downstream support wire 32 and then join, to desirably improve streamlining. Figure 46 illustrates another embodiment in which the thin strips 32 may abut to or overlap one or both of the support wires 36. Optionally, the thin strip 32 could be press fit around at least one of the wires 36.

In some configurations, the strip(s) 32 are preferably perforated after assembly of the compound tube 200 to facilitate assembly. These methods commonly form outwardly increasing orifices. (See, e.g., Figure 5.) In other embodiments, the thin strips 32 are perforated before assembly to facilitate movement of the strip(s) past a laser and to form orifices with larger openings within the tubes and smaller opening on the outside of the tube. I.e. inwardly increasing orifices. (See, e.g., Figure 6.)

In some embodiments, the thin wall strip(s) 32 are formed into a desired curve prior to assembling and bonding them to the support wires 36. Alternatively, in some assembly methods, the wall strip(s) 32 are assembled flat and the fluid within the compound tubes 200 is pressurized to a desired forming or proof pressure to curve the strips.

In some embodiments, the stiffening wires 36 are moderately flattened to improve bending stiffness and provide a greater surface to bond to the thin strip, though circular wires may be used. In other embodiments, trapezoidal shaped wires may be used to improve bonding while still providing some streamlining. In modified embodiments, the upstream or downstream

end of the supporting wire 36 may similarly be formed to improve streamlining. Similarly, in some embodiments the edges of the thin strips 32 may be cut at an angle, thinned, beveled, pressed, ground or otherwise smoothed to improve aerodynamics.

10.14.3 Polygonal Wired Tubes

In embodiments utilizing triangular or other polygonal shaped contactor tubes 10, this method may be used to provide a wire support at each vertex of the polygonal tube.

10.15 Alternative Assembly of Compound Perforated Tube After forming the structural strip and the stiffened perforated foil as described above, the following modified or other techniques or steps are used in some embodiments. (See, for example, Figure 43, Figure 44.)

10.15.1 Attach perforated foil to structural strip

Overlap and align one edge of the perforated foil over the indented edge of the structural strip. Users preferably reduce hole blockage and facilitate cleaning by using the "horn" configuration. I.e. by orienting the smaller hole diameter inward with the hole size increasing outward (as discussed above and illustrated in Figure 5.) If the smallest holes are needed or desired, then users use the "funnel" configuration. I.e. users configure the smaller diameter of the holes aligned outward with the outer surface of the strip and larger diameter inward (as discussed above and illustrated in Figure 6.) In this assembly method, the perforated strip or foil is first bonded to the structural strip along one edge.

10.15.2 Form stiffened perforated foil into downstream streamlined shape

Both sides of the compound strip are bent up about the tube-foil joint and formed into the desired streamlined shape. This will be similar to an elliptical shape but with a wider shorter upstream width and longer narrower downstream section similar to aircraft strut faring.

10.15.3 Align perforated foil to structural strip

The free edge of the formed perforated strip is aligned to the indent in the formed structural strip.

10.15.4 Attach outer foil edge to strip edge

The perforated foil edge is attached or bonded to the structural strip edge to complete the

streamlined compound perforated tube.

10.16 Alternative Elliptical Tube Construction With reference to Figures 43 and Figure 44, following is a modified or other method of forming a compound perforated tube starting with an approximately elliptical tube.

10.16.1 Form Elliptical Tube

A stainless steel tubing of diameter D is pressed into an approximately elliptical shape. E.g., a tube with about a 4 mm outer diameter is selected with wall thickness about in the range 0.20 mm to 1.0 mm. This will have a circumference of πD of about 12.6 mm with a half circumference of about 6.3 mm.

10.16.2 Cut into Half Elliptical Tube

This elliptical tube is then cut in half along the short axis (normal to and half way along the long axis). E.g., using an abrasive water jet or a power laser. In other embodiments the tube is machined about in half to remove one half along this line.

10.16.3 Form elliptical foil

The thin perforated stainless steel foil is then formed approximately into the shape of half an ellipse with the ends forming the short axis of the ellipse. (In modified embodiments the tube is formed into a similar parabolic shape). This downstream tube section is formed slightly wider than the net width of the supporting upstream half tube.

10.16.4 Prepare Attachment Indent

A thin indent is then ground a little greater than the thickness of the perforated foil on each outer side of the half tube e.g., about 25 to 35 micrometers. This is extended a little greater than the desired attachment width of the foil. E.g., about 0.6 mm to about 1.1 mm up both outer edges of the tube.

10.16.5 Fit foil to tube

The perforated foil half ellipse is fitted up over the half ellipse supporting tube to form an approximate ellipse.

10.16.6 Bond foil to tube

The thin foil half tube is then bonded to the supporting half tube. E.g., by induction

welding, friction welding, brazing, soldering or gluing among other methods, according to the temperature and strength required.

10.17 Hybrid Compound Tubes

Users may combine the various embodiments and assembly methods described herein.

10.17.1 Compound tubes from ground strips

In some embodiments, users may take a tube wall strip 30 and grid a thin wall section 32 along a portion of the strip. The thin strip section 32 is preferably perforated and then the strip 30 is assembled to form compound perforated tubes by the methods described herein. This method provides benefits of achieving more uniform thinned strip thickness. Correspondingly this results in more precisely sized orifices or uniform orifices being formed by the laser drilling or other orifice forming technology. Alternatively, the thin sheet ground walls 32 may be perforated after assembling the tube.

10.17.2 Wire tubes from ground strips

With reference to Figure 49, in modified embodiments, users form one or more thin wall sections 32 from thinned strips around wire stiffeners 36 to form a stiffened thin wall tube 200. This method provides very thin walls and small orifices while giving substantially greater structural strength, stiffness and streamlining or widening.

10.18 Combination Thinning & Drilling

With continued reference to Figure 49, in some embodiments, users reduce the thickness of tube walls 30 to form thin walls (not illustrated) using controlled thinning methods (other than grinding) such as lasers, electrochemical etching or photochemical etching as described above. Orifices 80 are then formed through the thinned sections 32 using technologies such as high resolution laser drilling (as described above). With such methods, users need only make moderate diameter pits to form thin walls 32, rather than thinning continuous or extensive sections of the tube 30.) This advantageously removes less material and retains more of the wall strength than other grinding or thinning methods that thin larger wall sections. This method can utilize conventional lasers with moderate thickness/depth ratios to form orifices 80 rather than very high thickness to diameter (T/D) ratios. E.g., using T/D ratios typically of about 7 to 50

instead of about 50 to 200.

10.19 Other Configurations Of course, as the skilled artisan will appreciate, other suitable nominal thicknesses and shapes may be efficaciously provided for the upstream and downstream structural components 36, 38 (or "wires") used to form the compound perforated tubes. Similarly, as the skilled artisan will recognize, a variety of curved, curvilinear, angular or flat strips 32 may be used to form the side walls 33 of the compound perforated tubes 200. Various combinations of the thinning and/or forming holes may similarly be used, as desired or needed. Furthermore, orifices 80 may be positioned in a variety of locations and orientations about a thin-walled tube 8 or compound perforated tube 200 depending on the pressure drop and degree of mixing desired or needed.

11 FLUID DELIVERY SYSTEMS

Figure 1 illustrates an exemplary embodiment of a fluid delivery system that may be used in combination with the embodiments described above. In general, the fluid delivery system comprises a first fluid delivery system 360 for delivery fluid to the first flow path, a second fluid delivery system 400 for delivering the second fluid to the second flow path and a control system 588. mentioned above, the first and second fluids may be any combination of a gas, fluid, fluid with gas or solid suspension or any combination thereof. With reference to Figure 61, the first fluid delivery system 360 may include a first fluid supply 356, such as a source of clean water. The second fluid delivery system 400 may include a second fluid supply 390, commonly the atmosphere, but it could be oxygen enriched air etc.

11.2 Fluid Filters

Further referring to Figure 61, to effectively use fine orifices, in some embodiments, users preferably filter one or more fluids from coarse and fine particulates sufficient to prevent them from substantially blocking the fine distributed orifices in the contactor array 260 through which those fluids are delivered.

Besides filtration, water treatment such as by mixed-bed demineralizers may be required. Other types of treatment such as reverse osmosis and other types of demineralizers can be used where the chemistry is suitable. These treatment methods can remove any chemicals that are

incompatible with the components into which it will be injected, e.g., turbine hot path.

11.2.1 Coarse Fluid Filter

For example, in the illustrated embodiment in Figure 61, users preferably begin filtration by providing using inexpensive coarse fluid filters 380 upstream of the first fluid storage tank 362 and before or after the supply pump to remove the bulk of any particulate material in the fluid being filtered in the beginning or initial filtering stages. E.g., coarse filters appropriately configured to filter the first fluid. Duplex coarse filters are preferably the duplex type such that filter media can be cleaned or replaced on-line when other filter in the duplex arrangement is used. Automatic backwash filters media filters down to 100 microns are also available. The coarse filter system may include a settling or break tank upstream of the coarse filters. This can hold the first fluid such as water for start-up as well as serve to settle-out large particles, lessening the load on the filters.

11.2.2 Fine Fluid Filter

In the exemplary embodiment, users further preferably follow the initial filter 380 with finer filter(s) 380 capable of filtering off smaller particulates, preferably capable of filtering particulates smaller than the diameter d of orifices 80. This provides an inexpensive means to protect the orifices and any subsequent filters. E.g., fine filters appropriately configured to filter the first fluid. Media filters (e.g., sand, anthracite) may also be used to filter particulates out down to around 10 microns.

11.2.3 Maximum Orifice Fluid Filters

With continued reference to Figure 61, users preferably provide fine maximum size fluid filters 386 (e.g., uniform orifice fluid filters) to further remove particulates and protect the orifices in the contactor array 260 from being progressively blocked by particulates. For example, users form such maximum orifice filters 386 using numerous fine orifices of uniform size. The fluid is preferably passed though such maximum orifice filters 386 prior to the fluid entering the perforated tubes. The maximum particle size passed by the fine filter may be in the range of 10% to 90% of the orifice size. The maximum particle size is more preferably 2/3^{rds} (or about 67%) of the orifice size or less.

Users preferably form this maximum orifice fine filter 386 using a filter membrane or sheet with a large number of accurately controlled uniformly sized orifices. This can be formed by suitable hole drilling technology, e.g., laser orifice drilling or photo etching similar to making the tube orifices. Users preferably configure large numbers of uniform orifices in large thin flat sheets to achieve a low pressure drop across the filter sheet. The number of orifices and net orifice area in this filter sheet are preferably in the range of 1.1 to 200 times that of the orifices in the direct contactor array 260. More preferably these are in the range of 5 to 50 times, to reduce the total costs of filtration and the filtration pumping costs.

In some embodiments, users then preferably support the sheet with a porous backing that permits the liquid to flow through while supporting the filter membrane. These uniform orifice filter sheets may be variously configured into maximum orifice filters 386. These may be configured like plate heat exchangers or wrapped into spiral formats similar to reverse osmosis filters.

11.2.4 Recirculating "Bypass" Filter(s)

With continued reference to Figure 61, to extend the life of the main filters (including one or more coarse filters, fine filters, and maximum orifice fine filters 386, the users preferably also process storage tanks 362 with bypass recirculation filters 380 to pick up most particulates in secondary inexpensive intake filters 380 which need not have the absolute maximum orifice size of the maximum orifice fine fluid filters 386.

11.2.5 First Fluid Delivery System: e.g., Liquid Pump

With further reference to Figure 61, users preferably provide first fluid delivery system 360, including equipment to pressurize and deliver the first fluid through orifices in the contactor array 260. Users preferably select equipment sufficient to at least overcome the pressure drop of the fluid through the contactor tubes, the pressure drop of delivering the first fluid through the orifices, the pressure drop needed to exceed the pressure of the second fluid at the first fluid orifices, the differential surface energy, and to eject the first fluid into the second fluid to a desired penetration distance. As the first fluid is more commonly a liquid (e.g., water or diesel fuel), users preferably configure the first fluid delivery system to include a pump capable of

generating at least the maximum pressure, flow rate and turndown rate desired.

Conventional horizontal centrifugal or vertical turbine type pumps are readily available in the flow and pressure range required and can be used as one or more pumps 364 where appropriate. Where the pressure or flow control or both is needed, flow control valves on the pump discharge may be used. In some embodiments, users preferably use a continuous positive displacement pump that creates very low pressure fluctuations for the pump 364 to improve fluid delivery performance. (E.g., Kraütler GmbH & Co. of Lustenau, Austria makes precision continuous positive displacement equipment ("KRAL") that can be used as a pump or as a flow meter.)

Two pumps are preferred. The first is a low developed head pump. It takes suction from the source of the recycled water (a tank or other vessel) and pumps the water through the filter(s), water treatment equipment, and heat recovery equipment etc. to the suction of the second pump. The piping, pump, and equipment from the water source through to the second pump, are of low pressure rating and hence low cost. The second pump preferably has a high developed head (e.g., 165 bar) to produce the pressure needed at the first fluid orifices and associated intermediate heat recovery components as needed. The piping and equipment downstream of the second pump are of high pressure ratings. Piping is kept as short as possible to minimize the cost of the heavier piping and to minimize pressure losses in the pipe.

11.2.6 Pump Pressure Fluctuation Dampers

With reference to Figure 61, in various embodiments, oscillations of differential ejection pressure across the distribution tube orifices 80 between the first fluid 901 and the second fluid 904 can cause variations in flow of those first fluid 901 through those orifices. E.g., a typical positive displacement high pressure Diesel pump creates very substantial pressure pulsations in the diesel fuel. These cause pulsating variations in the ratio of the flow of first fluid 901 delivered to the flow of the second fluid 904. As such, as shown in the embodiment of Figure 61, users preferably provide pressure modulators 370 to reduce these fluctuations. E.g., pressure or flow fluctuation dampers between the source of the pulsations (e.g., the pump) within the fluid delivery system 360 and the fluid distribution orifices. These dampers 370 are preferably

configured to significantly reduce these fluid oscillations and the corresponding variations in ratio of the first fluid to the second fluid, and/or the third fluid to the second fluid.

11.2.7 Fluid Flow Transducer

As shown in Figure 61, users preferably provide a high accuracy high resolution fluid flow transducer inline between the first fluid pump and the manifold to the distribution perforated tube array 260. In some embodiments, users preferably use a continuous positive displacement liquid flow transducer with a an accuracy about 0.1% and a resolution about 0.01%. E.g., the continuous positive displacement high precision flow meters from KRAL-USA of Redland CA. These are used as secondary liquid flow transfer standards as well as being used with a wide range of liquids and liquid viscosities in commercial applications. In other applications, users use lesser flow transducers with resolution about 0.1% etc. Similarly, a differential pressure monitor may be used on either side of a venturi or calibrated flow aperture to monitor flow rates.

11.2.8 Further Fluid Treatment

In some configurations, users provide further fluid treatment beyond filtration as desired or required by system components. E.g., water treatment such as by mixed-bed deimineralizers may be provided. Other types of treatment such as reverse osmosis and other types of demineralizers can be used to achieve desirable composition and fluid purity as appropriate. Such fluid treatment removes chemicals that are incompatible with the components into which the fluid will be injected, e.g., turbine hot path.

11.3 Second Fluid Delivery System

In many embodiments, the second fluid 904 delivered is commonly a gas. (In other embodiments these methods may apply to delivering a first fluid into a second liquid.) Accordingly, in such systems as shown in Figure 61, users preferably provide a second fluid delivery system 400 to create a pressure difference in the first fluid 904 between the fluid delivery location at the duct intake 134 and the fluid exit location at the duct outlet 136. E.g., providing a suitable pressurizing device, such as a compressor 407 or blower, to create a pressure difference in the compressed air between the combustor inlet 134 and the combustor outlet 136.

Users create sufficient pressure difference to move the gas through at the desired flow rate when constrained by the flow impedance between the combustor inlet 134 and outlet 136.

11.3.1 Blower(s)

As shown in Figure 61, users sometimes configure one or more low pressure compressors 407 or "blowers" within the second fluid delivery system 400 prior to the fluid contactor tubes 10 to generate the prescribed pressure differential between the gas delivery point (e.g., combustor inlet 134) and the combustor exit 136. In other embodiments users place the blower after the fluid contactors 10 to generate a prescribed draft or negative differential ejection pressure.

11.3.2 Compressor(s)

In energy conversion systems, with reference to Figure 84, for higher pressure applications, in other embodiments, users preferably configure the second fluid delivery system to include one or more compressors 407, in series prior to the fluid contactor to generate the prescribed pressure differential between the gas delivery point and the contactor exit.

In some power embodiments, turbomachinery is commonly used to compress the gaseous fluid 904, e.g., using centrifugal or axial compressors. These are preferably for applications operating at high duty levels over relatively narrow speed and flow ranges.

11.3.3 Moving Cavity Compressors

As shown in Figure 1 and Figure 61, users may configure the second fluid delivery system 400 to include precision screw compressors 407 or other moving cavity compressors to compress gases with high efficiency and linearity over a wide turndown ratio. These typically have three lobes, giving three pulses in the gas pressure per rotor revolution. (E.g., E.g., Kobelco Compressors (America), Inc. of Elkhart, Indiana, provides compressors claiming about +/- 1% linearity over a turn down range from the design flow of 100% down to about 10% of design flow or less).

11.3.4 Natural Draft Device

In other embodiments users may configure the second delivery system 400 to provide the motive power to deliver and move this second fluid 904 through the fluid contactor 10 by use of device or system that generates a natural draft such as a stack, chimney or flare.

11.4 Fluid Delivery System Control With reference to Figure 1, and Figure 61, as mentioned above, the fuel system preferably comprises the first fluid delivery system 360, the second fluid delivery system 400 and the controller 590. The controller 590 preferably controls and monitors the overall operation of the system such as pump developed head, pump speed, speed of the compressor 407 and/or blower, fluid flow rate, and fluid temperatures. Suitable sensors may be utilized, such as rotational speeds, pressure, temperature, flow meters and the like, as needed or desired. The controller may efficaciously incorporate a feedback system.

In various embodiments, pumps, blowers and/or compressors 407 are variously driven by work engines, synchronous or asynchronous motors with fairly constant or varying speed. Where the pressure or flow control or both is needed, flow control valves on the pump discharge may be used. Variations in drive speed, atmospheric pressure and/or humidity cause small but significant differences in composition and/or the pressure and/or temperature to which the second fluid is compressed. In various embodiments, users preferably improve control over the compressor speed to improve control of the pressure, flow rate and/or temperature of the second fluid supplied to the fluid contactor.

11.4.1 Variable Speed Drive

In some embodiments, users preferably drive the fluid supply system by a electrical, mechanical, hydraulic or pneumatic variable speed drive and/or the pump stroke. Users preferably provide a synchronous motor and use variable frequency drive and control system to reduce the variation in drive speed with variations in pressure differential between atmospheric pressure and the pump head or pressure supplied. Electronic speed control with induction motors may similarly be used. In other embodiments users provide an asynchronous motor or work engine such as a gas turbine or an internal combustion engine.

Alternatively, standard pumps with flow control valves may be used where more economical than variable speed drives. Flow sensors such as venturies, nozzles, or orifice plates with differential pressure transducers would be used with single loop or other types of controllers to vary the flow according to demand, automatically or manually.

11.4.2 Drive Speed Transducer

Users preferably provide a speed meter 580 as shown in Figure 61, to monitor the speed of the pump(s) 364 and/or compressor(s) 407 delivering one or more of the first fluid 901 and second fluid 904 (e.g., diesel fuel or water and air). In some embodiments users preferably control fluid supply drive speed to about an order of magnitude greater precision. E.g., users preferably control to about 0.01% to achieve uncertainty of the order of 0.1% in some configurations. In turn, users preferably provide a speed meter or rotary transducer 580 with substantially greater resolution than the desired degree of control. E.g., In some embodiments users preferably provide a high resolution rotary transducer close coupled to one or more pump drive shafts of the order of 0.001%.

High resolution speed meters 580 such as rotary encoders are available. E.g., optical encoders with 10,000 optical pulses per revolution are preferably used. Electronic conditioners are available to multiply that pulse rate 2 times to 20 times. In some embodiments, users preferably use such rotary encoders 580 to provide about 200,000 pulses per revolution for design speeds of about 20 Hz (1200 RPM). They preferably utilize dithering electronics to reduce errors due to vibration. (e.g., (E.g., such equipment is provided by BEI Electronics with a 10,000 pulse per revolution encoder and a 20 x pulse multiplier). Such pulse resolution is reduced as needed to accommodate the desired design rotational speed. E.g., for 4 MHz electronics with 100 Hz pump speed (6,000 RPM), users preferably keep the electronic frequency to about 40,000 pulses/revolution such as by using 10,000 pulses/revolution with a four times electronic multiplier.

Similarly, users preferably provide a high resolution speed meter 580 for one or more compressors 407 to assist in monitoring the flow rate of the second fluid 904 (e.g., the oxidant fluid). They preferably add a differential pressure sensor monitor across the second fluid compressor(s) and the first fluid pump(s) between the fluid intake and fluid delivery ports, and an absolute pressure intake sensor, or equivalently two absolute pressure sensors. Corresponding temperature sensors are also provided. These assist in precisely controlling the delivery fluid flow rates.

11.4.3 Drive Controller

As shown in Figure 61, in the illustrated embodiments, users preferably control the respective speed of one or more of the fluid pumps 364 using feedback from speed meters 580 with one or more controllers 590, to control the first fluid delivery system and the second fluid delivery system. These controllers preferably can accommodate the resolution and precision of the speed meters and other transducers, among other parameters. The controller(s) may be any type of control system in the art and may include for example one or more programable computers with associated control routines, hard wired control circuits, etc. The controllers 590 preferably incorporate digital control providing the capability of compensating for system non-linearities and flexible control algorithms.

11.5 Selective Orifice Fluid Control via Intra-Tube Fluid Pulsation

In some applications desiring low flows with low differential ejection pressures, users control the differential orifice pressure across the tube wall 30 to selectively control when the first fluid 901 is delivered and through which orifices 80. Such control is selectively combined at the low end of flow control to improve the turn down ratio and range of flow control in some embodiments.

11.5.1 Minimum Orifice Differential Fluid Pressure to Overcome Surface Energy

With small orifices, surface tension becomes a significant factor in determining drop (or bubble) formation out of orifices 80. A differential ejection pressure (or acceleration) is typically needed to form liquid drops or micro-jets (in a gas or liquid) or conversely gas bubbles in a liquid, due to increasing the interfacial surface energy ("surface tension"). The higher the interfacial curvature (the smaller the orifice diameter), the greater the differential ejection pressure needed to form the interfacial surface energy. When orifices vary in diameter, there is a **Minimum Orifice Differential ejection pressure** needed to expel liquid from the largest holes 80. This will typically be insufficient to expel fluid from smaller orifices 80.

Accordingly, as shown in Figure 73, users apply at least the Minimum Orifice Differential ejection pressure sufficient to expel liquid from the smallest orifices 80. Users correspondingly provide fluid pressure in the manifolds 240 and contactor tubes 10 at least sufficient to exceed this minimum differential ejection pressure at the tube orifices 80 when users need or desire to

create drops or micro-jets. This fluid flow continues through orifices 80 as long as that first fluid 901 is provided with at least a differential ejection pressure greater than this Minimum Orifice Differential ejection pressure.

11.5.2 Partial Orifice Differential Fluid Pressure

In other embodiments, as shown in Figure 73, users apply a **Partial Orifice Differential Fluid Pressure** that is generally less than All Orifice Differential Fluid Pressure but somewhat greater than the Minimum (Largest) Differential Fluid Pressure, as needed or desired. By such pressure control, users form drops or micro-jets from the larger orifices but not from the smaller ones.

11.5.3 All Orifice Differential Fluid Pressure

When orifices 80 differ in size about the distribution tubes 10, then to create drops or micro-jets (or bubbles) users preferably control the differential ejection pressures or accelerations applied across the orifices 80 (or tube wall 30) between the fluid 901 within the tubes 10 and the surrounding fluid 904 to selectively create drops or micro-jets (or bubbles) from differing sized orifices 80. As shown in Figure 74, in some embodiments, users preferably apply a pressure generally greater than the **All Orifice Differential Fluid Pressure** or acceleration sufficient to form drops or micro-jets through all the orifices.

11.5.4 Control by graded differential ejection pressure

In other embodiments, users form orifices 80 with a small but generally uniform gradient in size e.g., large at the center to smaller at the periphery. (See, e.g., Figure 9 and Figure 10.) As shown in Figure 75, users then apply a prescribed differential pressure sufficient to form drops or micro-jets though a portion of the orifices but not through all of them, in order of larger orifices to smaller ones. I.e., they apply a **Partial Orifice Differential Fluid Pressure (Podp)** to selectively control the drop and micro-jet formation through some but not all the graded orifices 80. In some embodiments, users selectively control the differential ejection pressure to spatially select where drops or micro-jets are formed. To do so, they preferably vary the differential ejection pressure at least above a minimum pressure and generally below the maximum pressure required to form drops or micro-jets from all the orifices 80.

11.5.5 Control by Pressure with Discrete Orifice Sizes

In some embodiments, users form orifices 80 of varying size for contactor tubes 10 bent to different radii, arcs or helices. As shown in Figure 75, a prescribed differential ejection pressure is then applied to selectively issue or eject drops or micro-jets (or bubbles) from orifices 80 in some contactor tubes 80 and not from others. This provides users with fairly discrete spatial control of where drops or micro-jets are formed.

11.5.6 Control by Digital Fluid Pulsation

With fairly uniform orifices, in some embodiments, users use a differential ejection pressure pulse as a pressure "switch" to form one or more drops or micro-jets of a first fluid 901 out of each of a prescribed range of orifices 80 as shown in Figure 76. They then turn the flow off by reducing the differential ejection pressure to somewhat below the minimum orifice differential ejection pressure.

11.5.7 Control by Frequency Modulation

By varying the frequency of fluid pulses of a given magnitude to the fluid 901 within the contactor tubes 10, in some embodiments as shown in Figure 77, users apply a frequency modulation of drops or micro-jets (or bubbles) injected into the surrounding fluid flow. The rate at which drops or micro-jets are formed is generally controlled by the frequency with which a pressure pulse is given that exceeds the Minimum Orifice Differential ejection pressure. To refine this control, users preferably provide smaller changes in the pulse width to compensate for inertia and the necessary fluid acceleration needed to form a drop or bubble.

In another variation users provide pulse width modulation (PWM) control of the differential ejection pressure and thus of the delivery of the first fluid through the orifices, as shown in Figure 77 and Figure 78.

11.5.8 Control by Amplitude Modulation

By varying the amplitude of the differential ejection pressure across the contactor tubes 10, in some embodiments users create a form of amplitude modulation. With intermediate differential fluid pressures, the higher the pressure the more orifices 80 emit liquid. As shown in Figure 78, with pressures above the All Orifice Differential ejection pressure, the higher the

differential ejection pressure, the greater the velocity and rate of fluid ejected through the orifices 80. Above the All Orifice Differential ejection pressure, users control the fluid flow about in proportion to the square root of the applied differential ejection pressure.

Users further vary the width of pressure pulses to provide some degree of amplitude modulation because of fluid inertia and the time it takes to accelerate and expel liquid through the orifices 80 in some configurations. I.e. using pulse width modulation (PWM).

11.5.9 Higher Pressure Jet Control

By increasing the differential ejection pressure across the tube wall 30 above that required to form fluid drops or micro-jets, in some embodiments as shown in Figure 78, users increase the flow rate of the injected first fluid 901 until it forms a jet with a desired velocity entering the second fluid flow 904. This affects the drop size, injected fluid flow rate and jet penetration distance. Users further control the fluid injection rate by adjusting this high differential ejection pressure within the working design stress limits of the contactor tube 10 and construction of orifices 80.

11.5.10 Maximum Operating Design Pressure

The strength of the thin wall strip or foil, orifice fraction and wall curvature, will have effect on the limit of the usable differential ejection pressure across the perforated wall. Accordingly, in some embodiments, users generally limit the upper differential ejection pressure within suitable safety factors of the maximum burst pressure, accounting for long term cyclic fatigue of the contactor tube 10 or compound contactor tube 200. (See, for example, Figure 73.)

11.5.11 Pressure difference in compound perforated tubes

With compound tubes, the thin walls will be the limiting factor on the pressure difference across the tube walls. However, much of the bending strength is preferably taken up by the structural tube portion. For thin perforated walls users preferably provide reinforcing supports outside of the thin perforated walls. This transfers much of the internal fluid load to the reinforcing supports.

Users preferably conduct a full finite element analysis to adjust the dimensions for the required flow and pressure differences. In other embodiments, other suitable modeling and/or

computation techniques empirical or semi-empirical studies and/or correlations, and the like may be efficaciously utilized to adjust dimensions, as need or desired.

11.6 Control by Spatial Phase Modulation

In some configurations, users configure orifices 80 with periodic spacing along a contactor tube 10. Where orifices are configured circumferentially around the tube, users preferably configure such orifices in a columnar arc around the contactor tube 10. Users further provide high frequency mechanical excitation to the first fluid 901 near the juncture of the tube to the manifold 240 or sub-manifold 254. (e.g., ultrasonic or acoustic.) They form a standing wave in the fluid within the contactor tubes 10. They preferably control the orifice spacing and the frequency of the mechanical excitation such that the orifice spacing H is equal to the wavelength of the fluid within the contactor tube 10, or some multiple of it.

Users then preferably control the relative phase of the excited standing wave in the first fluid 901 within the contactor tube 10. For maximum ejection, users adjust the phase of the standing wave is such that the fluid anti-node approximately matches the orifice locations. This causes the differential ejection pressure to be at a maximum at the orifice and a minimum at the node between the orifices. This results in a maximum differential ejection pressure and fluid ejection rate.

Similarly by adjusting the phase by about +/- 90 degrees, users adjust the relative phase of the excited standing wave in the first fluid within the tube 10 is adjusted to position the fluid pressure nodes at the orifices. This creates a minimum differential ejection pressure across the orifices. Accordingly this gives the minimum ejection flow for variations in pressure oscillation phase.

These measures provide rapid amplitude control over the fluid flow by control of fluid excitation wavelength and amplitude using the mechanical fluid excitation. The control resolution and speed are adjusted by the excitation frequency and orifice spacing, and excitation (amplitude or pressure) relative to the total differential pressure desired. These measures are preferably combined with one or more other pressure flow control measures to provide enhanced control flexibility.

11.7 Tube Stress and Differential ejection pressure Control

In various embodiments, users preferably control the maximum pressure difference across the tube wall 30 to stay within the design stress for the perforated tube 10, and prevent the tube 10 from bursting. The hoop stress generated in the tube walls 30 is preferably kept below the design working stress of the tube material accounting for the desired the operating temperature, the operating life and operating pressure oscillations. These are preferably adjusted for the stress concentrations of the orifices 80, and for tube forming and bonding methods and the drag of transverse flows across the tube. Users preferably maintain the fluid pressure to maintain a maximum tolerable design differential fluid pressure and pressure fluctuation rate within the contactor tube 10, based on the curvature, stress concentrations, temperature and operating strength of the tube wall 33.

11.7.1 Maximum Differential ejection pressure in Perforated Tubes

In general users preferably constrain the internal fluid force within the tube 10 to less than the tensile force in the tube walls 10 adjusted for operating and safety parameters. Users preferably use the Lame burst formula incorporating both internal and external tube radii to account for the influence of relatively thick walls. Alternatively, they use the Barlow burst formula for thin wall tubes. E.g., approximating by calculating the tensile force is about equal to the hoop stress in the tube wall 33 multiplied by the cross-sectional area of both tube wall sections in that longitudinal plane, where the internal fluid force is about equal to the fluid pressure times the longitudinal cross-sectional area of a tube section in a plane through the tube axis.

In doing so, users preferably account for the stress, creep and fatigue components. These include stress concentrations due to orifices, non-circular shapes, bending forces of gases traversing the flow, vibration due to turbulence and vortex generation, pressurization to control flow, and cyclic pressurization to vary flow rates or digitally control the liquid flow.

Under some circumstances and embodiments, users control differential ejection pressures to higher than the nominal design limits, but which remain below the tube burst pressure, when emergency flow rates higher than nominal design rates are desired or needed. They then replace

the distribution tubes more frequently to accommodate the greater damage rates.

11.7.2 Maximum Thin Wall Tube Diameter for Orifice Size

A given drilling technology (such as laser drilling) typically has a design Wall Thickness/Orifice Diameter (T/D) ratio. E.g., about 10:1. In various embodiments, users preferably select a desired orifice size. This in turn limits the maximum wall thickness through which users can create the needed or desired orifices using that orifice forming technology. E.g., about 100 micrometer (μm) wall thickness to form about 10 μm orifices with 10:1 T/D, or about 2 mm wall thickness with a 200:1 T/D etc.

11.7.3 Minimum Pressure for Liquid and Orifice

Conversely, users preferably determine a minimum pressure needed to force the liquid out through the orifices 80 based on the orifice size and the fluids 901 used. This is a function of the differential surface energy between the first liquid being expelled from the tube 10 and the second fluid 904 flowing across the tube 10.

In accordance with some preferred embodiments, users establish a minimum and a Maximum Differential ejection pressure within which embodiments of the distributed direct contactors 10 can be safely and / or desirably operated. They further preferably evaluate design minimum and maximum absolute or gauge pressures based on the operating pressure within of the distributed fluid contactor system 2. These are configured according to the fluid dynamics and system geometry including variations in pressure due to the fluid flows.

11.7.4 Maximum Over Pressure

In some circumstances, the pressure around the perforated tube 80 may fluctuate. It could be possible for the pressure around the contactor tube 80 to become greater than the pressure within the tube. In other embodiments the pressure within the perforated tube 80 might be decreased below the pressure around the tube 80. In such circumstances there is potential for a negative differential ejection pressure on the perforated tube 80.

Accordingly, in some embodiments, users preferably control the Maximum Negative Differential ejection pressure to prevent damage to a perforated tube 10 and/or compound perforated tube 200 from collapse or bending the tube wall 33 inward. This is particularly

applicable for tubes 80 within the pressurized chamber 170 with large oscillating pressures. e.g., such as within an internal combustion engine.

11.7.5 Tube End-end Differential pressure Profile Control

To increase control over the fluid delivery distributions and profiles along the contactor tubes 10, in some configurations as shown in Figure 17, users control the differential pressure between the adjacent connecting sub-manifolds 254 (or manifolds) across a section of a tube array 260. For example, users control the pressure across the shorter or longer sides of rectangular contactor array 266 or similarly between the inner and outer radii of an annular contactor array or between radial manifolds at the two ends of the annular array. For example, users provide pressure/flow modulators 370 at the entrance to each sub-manifold 254 to control and/or modulate the first fluid flow to the two sub-manifolds.

In a similar configuration, users provide a differential manifold pump to differentially pressurize fluid between the two sub-manifolds 254 (or manifolds) connected across or to the ends of contactor tubes 10. The differential manifold pump is preferably configured as a reversible pump with corresponding bidirectional controls so as to be able to generate an internal fluid gradient along the contactor tube 10 in either direction between the two adjoining sub-manifolds 254. In similar configurations, users provide controllable valves to control the flow through the two adjoining sub-manifolds 254.

Users accordingly configure the controller 590 to suitably control the Pressure/Flow Modulators 370 (or similarly the differential manifold pump, controllable valves) or as desired or needed, such as the control methods shown in Figure 73 to Figure 78. In some configurations they further configure the hydraulic diameter to length of the contactor tube 10. This varies the relative internal friction and degree of pressure drop along the tube from the flow.

By controlling the differential pressure in the connecting manifolds 240 or sub-manifolds 254, users control the internal pressure gradient along a contactor tube 10. They accordingly control the longitudinal distribution and profile along the tube 10 of the differential ejection pressure across the tube wall and associated orifices 80. Accordingly, they achieve a dynamic gradient in fluid delivery distribution and profile along the axis of the tube section 260 from one

end of the tube 10 to another. By controlling the differential pressure between the two connecting sub-manifolds 254, users preferably control the gradient of the first fluid 901 delivery distribution and profile within and along the direct contactor 10 delivering that fluid. E.g fuel fluid 901, and/or oxidant fluid 904.

11.7.6 Combined Pressure Profile Control

Preferably, in some embodiments, users combine such methods and variously control one or more of the mean differential ejection pressure amplitude across the tube wall 33, the gradient of the differential ejection pressure along the tube section 260, the dynamic fluctuating mean differential ejection pressure the fluid (e.g., the Root Mean Square value) in analog or discrete fashions, and the dynamic fluctuating gradient of the differential ejection pressure (RMS value) along the tube section 260.

Such control enables users to flexibly and precisely control the static and/or dynamic distribution and profile of the rate of fluid issuing from the tubes relative to the distribution and profile of the rate of fluid flow across the tubes 80. These can cover common turn down ratios or extend to very wide turn down ranges. For example, users may use pulse width, pulse amplitude, pulse frequency, analog and/or discrete variations in one or more of these differential ejection pressures such as depicted in Figure 73 through Figure 78.

With such controls 590, they dynamically adjust the flow rates to provide a wide range of methods to modulate the fluid flow and precisely control or meter one or both of the fluid flows, including digital, frequency, amplitude, pulse width or other modulation methods. In some embodiments, these are similarly used to modulate the relative fluid mixing as well as higher pressure fluid control.

11.8 Control of Fluid Ratio Profiles

With reference to Figure 18, Figure 19 and Figure 20, by controlling the relative transverse delivery distribution of the first fluid 901 relative to the transverse flow distribution of the second fluid 904, users preferably control the profile of the ratio between those two fluids across the contactors 10 or contactor arrays 260 over which users control the fluid pressures and consequent flows. In some configurations users control the profile of the ratio of the second fluid

to the first fluid in the first transverse direction to the second fluid flow 904 e.g., along the distributed members, or along a radial or other direction perpendicular to the duct axis. They similarly control this ratio profile in the second transverse direction to the second fluid flow 904; e.g., perpendicular to the distributed members, or circumferentially, or in another direction perpendicular to the duct.

In some configurations, users seek to form a fairly uniform fluid ratio profile along one or both of these transverse directions. E.g., to form a uniform ratio in the circumferential direction in an annular array. In other configurations, users will seek some other desired fluid ratio profile such as along the second transverse direction.

11.8.1 Oxidant to fuel ratio profile

For example, users preferably control the delivery distribution and/or profile of the fuel fluid 901 compared to the delivery distribution and/or profile of the oxidant fluid 904 to control the distribution and/or profile of the oxidant to fuel ratio across the contactors 10 or contactor arrays 260 in one or two transverse directions. Where users provide substantial excess oxidant containing fluid, controlling the oxidant to fuel ratio will correspondingly control the temperature of the combustion and resulting combustion gases or energetic fluid.

11.8.2 Water to air ratio profile

In another example, users preferably control the delivery distributions and/or profiles of water as a first fluid 901 compared to air flow as the second fluid 904 to control the distribution and/or profile of the water to air ratio across the contactors 10 or contactor arrays 260. This beneficially controls the relative humidity profile in the delivered air.

11.9 Vibrate Tubes-Orifices

With reference to Figure 50, in some embodiments, users preferably mechanically and/or electrically excite the perforated tubes 10 with an array or tube vibrator 50 to excite the perforated tubes 10 to generate vibrations in those tubes. This causes a sessile and then pendant drop or liquid jet to oscillate at or near the excitation frequency. This encourages drops to form with much greater precision and uniformity than by natural turbulence driven jet oscillation. Such measure facilitate drop formation and release, and to improve drop size uniformity or narrow the

drop size distribution.

The vibrator 50 may be mechanically and/or electrically excited such as using a pneumatic, hydraulic, or electromagnetic excitators. Correspondingly, users configure curvilinear flexible fluid supply tubes 54 that can deliver one or more of the first fluid 901 while flexibly accommodating the vibrations generated in the contactor tubes 10. The vibrator 50 may be inertially driven relative to a suspended mass. Alternatively, it may be supported between the surrounding structure and the contactor tubes 10 with tube supports 37 or similar supporting structures. Similarly the direct contactor array 260 is preferably supported by two or more flexible array supports 72 to the surrounding fluid duct 130 to permit the contactor array 260 to vibrate relative to the duct.

The vibrator 50 is preferably configured to excite vibrations generally perpendicular to the plane of the outlets of the orifices 80. E.g., preferably using axial excitation parallel to the fluid duct 130. This vibration preferably causes a sessile drop and then a pendant drop or liquid jet to oscillate at or near the vibrator excitation frequency. This vibration encourages drops to form with greater precision and uniformity than by natural turbulence driven oscillation.

11.9.1 Orifice Vibration Frequency & Direction

In some embodiments, users preferably oscillate one or both of the perforated tubes 10 or tube arrays 260 at or close to the natural frequency of the liquid micro-jet oscillation. In some embodiments, users preferably oscillate one or more the contactor tubes 10 along the axis of the axis of the fluid duct 130 or the predominant flow direction of the second fluid 904. This vibration axis is preferably selected when the orifices 80 are oriented predominantly perpendicular (normal) to that duct axis. In this mode, preferably all the orifices 80 are vibrated to desirably obtain more uniform drop size. In some embodiments, orifices expelling liquid drops or micro-jets are preferably vibrated transversely to the a vector predominantly parallel to the axis of the orifices 80 (e.g., the flow axis of the first fluid 901), especially when the orifice orientation is preferably perpendicular to the mean flow of the second fluid 904. This maximizes the formation of the capillary waves in the micro-jets and consequently encourages formation of drops or micro-jets of uniform size or more narrow size distribution.

In various embodiments, users preferably use a frequency Omega of wavelength lambda with a characteristic capillary speed V_c where Omega = V_c/lambda =V_c*0.56/(2*Pi*r_o).

In other embodiments, users preferably oscillate the tubes 10 transversely to the fluid flow direction of the second fluid 904 to create symmetric liquid oscillations. For example, when the orifices 80 are oriented parallel to the axis of the second fluid flow 904. In other embodiments, users vibrate the orifice array 260 in the azimuthal direction about the flow axis of the second fluid 904. As the orifice vibration magnitude is proportional to radial distance from that axis, this azimuthal excitation is most effective with annular array configurations 267, 269.

11.10 Differential Pressure Modulation System

As shown in Figure 1, in some embodiments, users provide a pressure modulation system 370 to vary the pressure of one or more fluids 901 flowing through the perforated tubes 10 or tube arrays 260. In modified embodiments, they may also or alternatively vary the pressure of the second fluid 904 flowing across the contactor tubes 10 or through the tube arrays 260. In some embodiments, users modulate the fluid pressure by varying the speed of one or more fluid delivery pumps 366 delivering a first fluid 901 or blowers 406 or compressors 407 to vary one or more of these pressures.

In other embodiments, users move diaphragms or walls of the fluid enclosure or duct, or pistons 197 or motion actuation members such as ultrasonic transducers connected to fluid manifolds and/or fluid ducts to modulate or fluctuate the pressure. In further embodiments, users combine such methods of pressure variation in the pressure modulation system 370.

By so doing, users preferably provide systems to control the differential ejection pressures across the perforated tubes and thus to control the fluid delivery rates through those perforated tubes.

11.11 Electrostatic Jet Reduction

Some embodiments of a direct fluid contactor incorporate electrostatic and/or electrodynamic jet reduction. In such embodiments, users preferably apply an static and/or dynamic electric field generally in line with the orifice axes. These arrangements may result in a substantial reduction in the diameter of liquid jets (such as liquid fuel or liquid diluent

jets) exiting the orifices. Consequently, the surface energy with this electrostatic deformation or modulation causes the jets breaks up into substantially smaller and/or more precise droplets than are typically formed from jets exiting those orifices under similar differential ejection pressures.

11.11.1 Electrical Field Excitation

For example, as schematically shown in Figure 79, users preferably provide a high voltage power supply 300 to deliver one or more high voltages to one or more distributor or combustor electrodes 320 or electric grids 326 and corresponding voltages to one or more tube electrodes comprising perforated tubes 10 or tube arrays 260 at some suitable distance displaced from the electrodes 320 or grids 326. In general, the tubes are preferably grounded by connection to a ground electrode 302, with the high voltage applied to the electric grid 326 by connecting it to a positive electrode 304 of the high voltage power supply 300.

In this example, users position a conical electric grid 326 positioned downstream of a conical distribution tube array 262 formed into a fuel fluid array electrode 322. By applying a differential high voltage between the downstream grid electrode 326 and the upstream fluid array electrode 322 will draw micro-jets from the tube orifices towards the electrode grid 326. The high voltage causes the jets to neck down and form smaller droplets. With sufficient voltage and small orifices, the droplets will be small enough to generally flow around the downstream grid 326 between the inlet 134 and the outlet 136.

As shown in Figure 80, in other embodiments, users similarly position the electrode grid 326 upstream of the grounded tubular distribution fluid array electrode 322. The electric field draws the micro-jets outward and generally upstream. Then the jets and droplets break up and are swept downstream by the transversely flowing second fluid. Correspondingly, in modified embodiments, users configure one set of contactor tubes as one electrode and ground it to a ground electrode 302. e.g., the fluid array electrode 322 preferably for any explosive fluids. They then configure a complementary contactor array electrode 322 and connect it to a high voltage electrode such as the negative electrode 306. Similarly, one set of contactor tubes may be divided with one set connected to one electrode (or ground), and the other set to the other high voltage electrode. In such configurations, the jets leaving one or more orifices 80 is attracted to the near by contactor electrode between the inlet 134 and the

outlet 136 (similar to the grid electrode 326 described previously.)

As shown in Figure 81, in other embodiments, users electrically excite the tube array 324 and first fluid delivery systems and connect the duct 130 to ground 302 between an inlet 134 and outlet 136. For instance, users may excite a cylindrical or conical array positioned within a cylindrical conductive duct. The duct acts as a grid and is conveniently grounded.

This high voltage excitation method requires relatively high voltages, but relatively low power. In some embodiments, the electric power supplies providing these voltages may be controlled to vary one or more of the electric voltages and/or currents. Both the mean and fluctuating amplitude, frequency and/or phase of the voltage are preferably controlled.

11.12 Electric Field Excitation Control

11.12.2 Base Electric Field Excitation

As mentioned above with reference to Figure 79 to Figure 81, in some embodiments, users preferably control the high voltage power supply 300 to desirably apply one or more suitable electric voltages to the respective electrodes 302-312 to generate electric fields generally normal to orifices 80 in perforated tubes 10. In some embodiments, one or more high differential voltages are applied between perforated tube arrays 260 and one or more complementary electrodes 326, 328, 330, 332, or 334 to form these electric fields. (See, for example, Figure 79.) In other embodiments, voltages are applied between two or more sets of distribution tubes 322, 324. (See, for example, Figure 80.) In another configuration, the voltages may be applied between contactor tubes 10, 322 or 324 and a portion of one or more ducts, 302, 320, 332. (See, for example, Figure 81.)

Users preferably apply such electric fields to reduce the size of liquid columns to smaller in diameter than the orifices 80 through which the fluids are delivered. Accordingly, they preferably break up the liquid column of first fluid 901 into micro droplets that are smaller than conventional drops, and preferably smaller than the diameter of the orifice 80. (This contrasts with sessile or "pendant" drops which form at about twice the size of the orifice 80. It also differs from high velocity jets which initially break up into drops of similar size to the orifice. The differential fluid velocity then variously breaks these drops into smaller droplets.) In such configurations, users preferably utilize one or more conductive manifolds 240 to electrically connect distribution tubes 10 to respective voltage sources at

electrodes 302-312.

In some embodiments, users preferably apply a prescribed, pre-selected or pre-determined excitation voltage(s) from the high voltage power supply 300 according to the electric field gradient desired or required, liquid surface tension and viscosity gas pressure and flow rates. They further account for the influence of the tube to tube gaps G, liquid composition and temperature(s). By using such electric field excitation, users seek to provide the benefits of using larger orifices 80 that are less susceptible to clogging while creating smaller drops and micro-jets. They can also use such methods to create drops or micro-jets from more viscous fuels such as bunker fuel or crude oil.

11.12.3 Control by Oscillating or Pulsing Electric Fields

In some embodiments, users pulse or oscillate the applied high voltage between two or more tubes 10 or tube sets 260, or between such tubes or arrays and electrodes 302-312, 320, 326-334. This provides an oscillating excitation to the first liquid 901 being delivered or expelled from the perforated tube orifices 80. This electric field oscillation in turn generates oscillations in the liquid column and initiates column breakup and droplet formation. The liquid excitation will be generally synchronous with the field excitation and may result in liquid oscillations synchronous with the electric field. Accordingly, users use the oscillating electric field excitation to generally create more uniform droplets according to the precision of pulsing the electric field in magnitude and frequency. The electric field and the fluid pressure modulation are preferably controlled together to have the greatest benefit in controlling the physical pressure oscillations and the precision of drop formation.

In some embodiments, users preferably tune the electric field pulsation or oscillation frequency to the natural liquid jet oscillation frequency in the presence of the average electrical field established. This further achieves more uniform drop formation.

11.12.4 Control by Field - Drop Frequency Modulation

As with pressure modulation, in some embodiments, users preferably modulate the electrical field to vary drop size and delivery rate with a prescribed frequency modulation.

11.12.5 Control by Field - Drop Amplitude Modulation

In some embodiments, users preferably modulate the amplitude of the electric field to expand or reduce the liquid jet as desired to create drops or micro-jets of differing size,

resulting in a general drop amplitude modulation. Similarly, users can use Pulse Width Modulation (PWM) to control the time over which the fluid is ejected. By using such amplitude modulation and pulse width modulation methods, they provide benefits of varying drop size and/or micro-jet flow in systems where drop size is generally controlled by the size of the orifices 80 and the surface energy of the first fluid 901 relative to the second fluid 904.

11.12.6 Control by Combined Frequency and Amplitude Field Modulation

In some embodiments, users combine frequency and amplitude modulation of the applied electric field from the power supply 300. This enables users to vary both drop size and drop delivery frequency and thus liquid delivery rate. In some configurations, users further combine electric field control with differential fluid pressure to desirably control drop size, drop or micro-jet delivery rates.

11.13 Electrostatic Homogenization

To more homogeneously distribute drops of a first fluid in a second fluid, users preferably use high voltage electrostatic excitation in some configurations. They preferably provide a high voltage power supply 300 and at least sufficient voltage and current between the direct contactors 10 or between contactors 10 and electrostatic grids 326, to charge at least 10% of the droplets formed, preferably more than 50%, and more preferably at least 90% of the droplets formed downstream of the direct contactors 10 within a prescribed drop formation residence time. By so charging the droplets and providing a desired residence time, they preferably cause the droplets to accelerate by mutual electrostatic repulsion caused by nearby drops having similar electrical charges. By charging the drops, users further shatter and disperse the drops of the first fluid 901 within the second fluid 904 when the charged droplets evaporate and reach a critical charge to mass condition.

Users preferably provide a desired drop homogenization residence time over which the droplets move driven by self-repulsion towards a smoother mass distribution and profile in one or both transverse directions, and in the axial direction relative to the fluid duct 130. By adding electrostatically charging the drops, users effectively provide a high frequency filter to at least one of the droplet distributions and/or profiles about the fluid duct 130. Users preferably select the drop homogenization residence time to achieve a desired degree of high frequency filtering or smoothing of at least one of the droplet distribution profiles along a

direction as well as the number distribution at a point. They preferably provide sufficient charging and homogenization residence time to effect at least about 10% smoothing preferably about 50% smoothing, and more preferably more than about 90% smoothing of the droplet spatial distribution and profile measured across about 20% of the respective duct dimension, e.g., radius, circumference, transverse width, transverse height, fluid duct length, bulbuous diameter as appropriate to the configuration of the contactor array 260.

By such high frequency electrostatic profile filtration, users advantageously improve the profile of the desired ratio of mass flow distributions of a liquid delivered through the contactor array 260, relative to a second fluid flowing within the fluid duct. E.g., the ratio of the mass flow distribution of fuel fluid 901 or diluent fluid 907 relative to the mass flow distribution of oxidant fluid 904. While this method most commonly applies to charging liquid fuel fluid 901 or liquid diluent fluid 907 through their respective contactors, it can also be used to charge and influence gaseous fluids.

11.14 Electrically Heating Contactors

In some embodiments, users electrically heat contactor tubes. In such embodiments, in reference to Figure 61, they preferably provide an electrical power supply 301 with suitable voltage and current to heat the contactor array 260 in a controlled manner. In such embodiments, users preferably connect the distributed fluid contactor array 260 to the power supply 301 using corrosion and temperature resistant electrical contacts. These contacts are preferably configured so that there are generally similar heating rates per surface area along the distribution tubes. In embodiments using one or more helical distribution tubes, users preferably connect the power supply 301 to each end of the distribution tubes.

The thermal cleaning is preferably performed when the system off duty with low flow rates of the second fluid to minimize the heating required. It may also be performed on duty with higher currents to compensate for higher cooling loads.

Similarly, in embodiments of contactor arrays 260 comprising multiple distribution tubes between manifolds, electrical contacts can be made symmetrically or asymmetrically across the manifolds so that the current generally flows uniformly from the power supply 301 through the contactor tubes. E.g., connecting voltages to manifolds on opposite corners of rectangular distribution arrays or annular arrays. In other embodiments non-uniform heating

is also used. With these various embodiments, the control system 588 preferably utilizes temperature sensors to control the heating to control the temperatures to which the distribution tubes are heated and the heating duration.

11.14.1 High Temperature Thermal Tube Cleaning

In some embodiments, users preferably make the perforated tubes 80 of high temperature materials capable of sustaining temperatures substantially greater than the pyrolysis temperatures of for example liquid fuels and blocking biomass materials. E.g., substantially higher than about 900 K (about 623°C or 1153°F). Correspondingly, users preferably keep the tube temperature below temperatures at which entrained ash and particulars melt to form slag that might block the orifices.

These measures preferably assist in removing fibers and other materials in the second fluid that come through the filtration system and build up on the contactor tubes and block the tube to tube gaps. Similarly unfiltered materials within the first fluid can block tube orifices.

In some embodiments with lower stress and temperature applications, users form the contactor tubes using high temperature stainless steel. In other embodiments, with higher stress and temperature applications, users preferably select Incolonel or Hastalloy or similar high temperature materials to form the contactor tubes.

11.14.2 High Temperature Cleaning Operation

In some preferred embodiments, further referring to Figure 1 and Figure 61, by using high temperature materials to make the contactor tubes, users preferably apply controlled electric currents from the power supply 301 to heat the tubes and vaporize or "gasify" any liquid fuel or biomass materials built up in or on the tubes 10 or blocking the orifices 80. This operation is controlled similarly to an electric "oven cleaner." Users preferably control the temperature carefully and precisely, sufficient to at least exceed the pyrolysis temperature of liquid fuels for the necessary duration. Users further preferably maintain the temperature below prescribed, pre-determined or pre-selected levels, to stay below creep and deformation design parameters of the material used, and preferably below salt melting temperatures or temperatures for slag formation from the deposits. They further control the duration of heating for sufficient time to sufficiently gasify the deposits. Such measures preferably

remove fibers and other material in the second fluid that are not filtered out can build up on the tubes and block tube to tube gaps.

In some embodiments, users preferably provide a flow of a reactive cleaning first fluid such as hot water or steam, through one or more perforated tubes in addition to or instead of electrically heating the tubes, to assist cleaning the orifices by the water gas shift reaction.

12 FORMING ARRAYS OF PERFORATED TUBES

Here are disclosed preferred methods of forming perforated distribution tubes. In some configurations, users further assemble these perforated tubes into contactor arrays and connect them to manifolds to duct the fluid to the tubes as described above.

12.2 Materials

In various configurations described above, the perforated tubes 10 and manifolds 240 may be formed from a wide variety of materials according to the applications, temperatures, and desired or needed design life. Embodiments commonly use corrosion resistant materials such as stainless steel. High temperature applications preferably use suitable high temperature materials such as Inconel or Hastalloy. Other embodiments can use quartz, glass, sapphire or ceramic. Other embodiments utilize a variety of structural plastics.

12.3 Cutting Tubes and Forming Holes Following are preferred ways of forming contactor tubes and manifolds, which may be used to form the embodiments described above. Other methods may also used.

12.3.1 Cut tubes

In one embodiment, users cut long lengths of tube into suitable shorter lengths. Technology is available to rapidly and precisely shear or separate tubes into shorter tubular lengths sections without sawing them and with minimal burr formation. E.g., Production Tube Cutting Inc. of Dayton Ohio.

12.3.2 Form manifold holes & shape tube ends

Referring to Figure 22, to attach distribution tubes 10 to manifolds 240, users form suitably sized manifold connecting holes 250 in the manifold wall 249. In many embodiments, users form circular holes 250 in manifold walls 249. Accordingly, users preferably form the ends of distribution tubes 10 into a circular shape to fit the manifold hole

250. Unperforated tubes are similarly attached.

In other embodiments, users may extend the manifold hole 250 to variously form round ended slots, or elliptically shaped holes etc. as needed or desired. Users correspondingly form the tube ends into shapes the conveniently fit into such elongated holes.

12.3.3 Friction drilling

Further referring to Figure 22, users preferably use friction drilling to heat and soften or melt manifold walls 249 and press a hole 250 through it where metal or similar ductile material is used. Users more preferably create a hole 250 and then pull the residual material out to form a collar. (For example, by using equipment from T-Drill company of Norcross, Georgia.) This method is preferably used to provide an outward extension that assists in welding a connecting tube 10 to the manifold wall 249 and adds strength to the joint. In other embodiments users may use methods of hot drilling to create a manifold hole 250, which leaves 80% of the residual metal pointing inward, 20% outward. (For example by using equipment from the FlowDrill company of St. Louis MO.)

12.4 Bond Tubes onto Manifolds Further referring to Figure 22, users abut or insert the tubes 10 into the manifold hole 250 in the manifold wall 249. Finally users join the tubes 10 to the manifold wall 249 at the manifold hole 250 by welding, brazing, soldering or by a similar suitable joining method. In some embodiments, tubes 10 are bonded to one or more manifold walls 250 using one of a variety of methods including inductive, electric or friction welding. Modern technology is now available to inductively weld small tubes 10 with thin tube walls 33 to manifold walls 250. (For instance, users may use equipment by VerMoTec of St. Ingbert, Germany which can inductively weld tubes with 0.15 mm thick walls.)

In other embodiments, users braze, solder, glue, thermo-form or use other suitable techniques to join the tubes 10 to one or more manifold walls 250.

12.5 Structural Supports Manifold Tube Supports

With reference to Figure 16 and Figure 17, attaching the perforated distribution tubes 10A-C to manifold walls 250 provides some structural support. Further support is provided by positioning tube sections between two manifolds 240 or sub-manifolds 254. E.g., in planar arrays, or in circular sections.

12.5.2 Additional supports

As needed or desired, users add further tube supports 37 at the end of tubes 10, or attach the tube supports 37 in between tube ends, preferably transversely to the tubes 10. In some embodiments, these support sections 37 are preferably positioned upstream of the tubes 10 so that liquid does not impact and build up on downstream supports. In other embodiments users attach tube supports 37 both above and below tubes 10 to form a three dimensional structurally supported array or space frame.

12.6 Three Dimensional Structural Supports

As the tubes 10 are offset along the axis of the fluid duct 130, so the manifolds 240 and structural tube supports 37 are also generally offset. Axially offsetting the tubes 10 and tube supports 37 advantageously forms a three dimensional structural support or space frame configuration that is stiffer and generally stronger than planar arrays.

12.6.1 Conical Ray Supports

As described above with respect to Figure 57, users form manifolds 240 and add further tube supports 37 in some embodiments as conical rays or radial rays about tangential to the surface of a conical tube array 262 or 264. By these methods, users provide three dimensional structural strength and stability to the tubular array 262 or 264. Users use at least two and preferably three or more radial structural manifolds 240 and tube supports 37 along the edge of the conical tube array 262 or 264.

12.6.2 Space Structure

In some embodiments, with reference to Figure 71, users further provide transverse tube supports 37 between tubes 10, and manifolds 240. Similarly, they may provide tube supports 37 between offset arrays 284 or similarly offset arrays 260-273. Such methods further create space array type structural supports, thus giving the contactor array 260 or 288 greater strength and rigidity.

12.7 Axially Multi-Plane Distribution Array

With reference to Figure 62, in some configurations, users preferably configure two or more sets of multi-tube distributor arrays each configured with desired transverse distribution(s) of orifice size, orifice spacing and orifice orientation transverse to the fluid duct. E.g., as multiple sets of annular arrays 267. As shown in the enlarged Figure 63, tubes

10 contain orifices 80 delivering fluid jets 903 across the tube to tube gap. Opposing orifices are preferably offset to give overlapping sprays.

These multiple contactor arrays 267 are then spaced axially along the duct to form an axially multi-plane distribution array. With further reference to Figure 62 and the enlarged view Figure 64, the contactor tubes 10 in each of these arrays are preferably oriented axially in-line to reduce drag by the second fluid 904.

As shown in Figure 64, users preferably configure differing mean transverse specific spatial orifice density distributions in the respective distributor arrays to give the greatest control flexibility. These spatial orifice specific areal density distributions are further configured to delivery the desired mass flow rate distribution of the first fluid, such as needed to achieve a desired transverse mass flow ratio of second fluid flow to first fluid flow.

Contactor tubes in each axially distinct array set 267 are preferably connected to corresponding sub-manifolds. Each sub-manifold 254 in turn is connected via pressure-flow modulators or valves to one or more manifolds 240. This permits at least on/off control of flow through the differing sets of axial contactor arrays. More preferably, each axially distinct contactor array set is preferably individually controlled to provide the greatest control flexibility and off design performance.

12.7.1 Jet Penetration Configurations

By varying the circumferential orientation of the orifices 80 about the perforated tube 10, users achieve differing jet penetrations across the tube-tube gap in some configurations. By starting with jet penetrations of about 10% to 200% of the tube-tube gap, fairly uniform mixing is achieved in the second transverse direction perpendicular to the tubes across a wide range of varying jet penetrations with varying fluid delivery flow ranges. Similarly, users vary the orifice size and consequently the relative jet penetrations in configuring the spatial orifice area density in some configurations.

12.7.2 Ranges of Varying Differential Ejection Pressure

The pressure-flow modulators may be configured to control the differential ejection pressure for a range of varying pressures. For example, where a precise narrow range of control is desired the pressure could be varied over about a 1.04:1 range giving about a 1.02:1 (i.e. 2%) variation in fluid flow. In another example, the differential ejection pressure range

can be configured for a range of about 2700 bar to 0.27 bar (40,000 psi to 4 psi) or 10,000 times pressure ratio. This gives an mass flow turndown ratio of about 100:1. Numerous pressure ranges within this range can be configured. The variation in mass flow ratio in relation to pressure flow ratio is shown for example in Table 5.

Table 5: Hybrid Turndown Ratio

	Mass Ratio						
Orifice Density Ratio	3.2	5.5	10.0	17.3	31.6	54.8	100.0
1.02	3.2	5.6	10	18	32	56	102
1.04	3.3	5.7	10	18	33	57	104
1.09	3.4	6.0	11	19	34	60	109
1.18	3.7	6.5	12	20	37	65	118
1.41	4.5	7.7	14	24	45	77	141
2	6	11	20	35	63	110	200
4	13	22	40	69	126	219	400
8	25	44	80	139	253	438	800
16	51	88	160	277	506	876	1,600
32	101	175	320	554	1,012	1,753	3,200
64	202	351	640	1,109	2,024	3,505	6,400
128	405	701	1,280	2,217	4,048	7,011	12,800
	10	30	100	300	1,000	3,000	10,000
	Pressure Ratio						

12.8 Hybrid Turn-down Ratios

By such combinations of varying spatial orifice density distributions, profiles and controls, users configure contactor arrays 260 which provide very wide turndown ratios of fluid flow profiles of the first fluid relative to the second fluid. For example, users may provide a 10:1 ratio in spatial orifice densities between one array and the next. They may further use a 10:1 flow turn-down ratio in each array by varying the differential ejection pressure by 100:1. The combination of two such arrays provides an effective 100:1 turn down ratio. By similarly adding a third array in like proportions, users achieve a 1000:1 turn down ratio for the combined array while only requiring a 100:1 pressure ratio range across each individual array. Similarly controlling the pressure range to 10,000 for a mass flow turn-down of 100 with three arrays of 10:1 range each gives a combined turndown ratio of 100x10x10x10 or 100,000. Such very wide turn-down ratios are achieved while generally preserving the transverse mass flow profiles of the delivered fluid. Other ratios may be readily used, as shown in Table 5.

13 HEAT EXCHANGERS & CONTACTORS

In various embodiments, users preferably configure one or more direct fluid contactor arrays to deliver a first fluid to mix with a second fluid to accomplish desired heat exchange processes comprising cooling, condensation, heating, and evaporation. Users preferably adjust one or more of the transverse distributions of contactor parameters of orifice size, position, orientation, tube spacing and fluid delivery pressure, to achieve corresponding desired transverse distributions of drop size distributions, jet penetration, and jet orientation. These in turn achieve desired transverse distributions of heat transfer rates, heat transfer distances, fluid flow delivery and fluid composition or second to first fluid ratio profiles. These are variously configured in one or more of the first and second transverse directions and the axial direction.

For example, in various embodiments such as shown in Figure 82, users preferably configure one or more direct fluid contactors or direct contact heat exchangers 483 to deliver a first fluid 901 to desirably contact a second fluid 904 with a desired degree of mixing. E.g., to configure a direct contact condensor 484.

13.2 Distributed Contactor Modeling Method

With reference to Figure 94, users preferably model and configure the first and second fluid flows to achieve one or more constraints and desired spatial distributions of fluid parameters or profiles or fluid parameter ratios. This method comprises setting up the appropriate boundary conditions such as one or more desired, prescribed or evaluated mean or spatial distributions of fluid mass flows, temperatures, pressures, densities, velocities, as appropriate to the model. They further provide orifice discharge coefficients, tube tensile strengths, tube dimensions and other relevant boundary conditions.

They further form equations to model the desired configurations. These include design equations for the tube parameters of tube length, tube to tube spacing, tube wall thickness/orifice diameter, orifice cone angle, etc. The spatial distribution of orifice parameters about the tube and across and along the duct are similarly modeled.

They further form the flow equations for the first and second fluids. These preferably include models of the flow through the tubes, through the orifices, spray penetration correlations and spray cone angle correlations. The equations include the desired composition mass or mol (or volume) flow rate relations either in the mean flows, or more particularly the

spatial distributions of compositions as desired or prescribed.

Users further apply desired or required constraints. For example, the desired transverse distribution(s) of spray penetration such as the degree of penetration across the tube to tube gap. Similarly the spatial profiles of the ratio of second to first fluid flow rates or equivalent spatial composition distributions. These may also include spatial constraints on the time to achieve desired fractions of heat transfer and/or on the corresponding distance distributions needed to achieve those fractions of heat transfer. For example, these may include the spatial distributions of evaporation time and/or evaporation distance. They further apply the constraints of tube strength and maximum burst pressure, realizable tube diameters, maximum orifice length/diameter ratios in drilling etc.

With these models, users then initialize parameters as needed by the computational methods. They further normalize or configure the equations into ratios to assist in convergence etc. In some configurations, the equations are configured into non-linear search programs as desired or needed to provide convergence.

Users then configure the programs to produce the desired output values and figures. For example, these include the spatial distribution(s) of fluid pressure, orifice number, orifice spacing, orifice diameter, orifice orientation, and orifice length/diameter ratio profiles. Similarly they obtain the spatial distributions of spray cone angle, spray penetration, injection velocity, differential ejection pressure and fluid compositions or profiles of the ratios of second to first fluid flow rates. They similarly obtain the desired distributions of tube to tube gap, wall thickness, diameter and length. These methods are further exemplified in the following discussions of configuring heat exchangers.

13.3 Residence Time

13.3.2 Residence time vs drop size distribution

The speed of many physical phenomena and chemical reactions depends on the surface area of a fluid, or the interfacial area between two fluids. The time for the process to finish in turn depends on change in a process through the drop and thus on the drop size. Drop formation in most prior art systems results in a broad distribution of drop sizes. Disadvantageously, this results in a broad distribution of corresponding drop reaction residence times. In the relevant art, systems are commonly sized for the largest drops or

micro-jets and longest acceptable residence times with large spatial variations resulting from a few jets.

In some embodiments, users advantageously configure a direct contact heat exchanger 483 or direct contact condensor 484 to form drops or micro-jets with prescribed distributions and/or profiles of orifice sizes in the transverse and/or axial directions relative to the fluid duct 130. Using the preferred methods described with respect to Figure 18, Figure 19 and Figure 20 and herein, they configure achieve desired transverse drop size distribution distribution(s), profile(s) and/or fluid delivery distribution(s) and/or profile(s) using distributed perforated tube arrays 260 of embodiments of the invention. In turn, users achieve a fairly uniform and/or more narrowly controlled distribution of residence times for most of the drops or micro-jets. Consequently, users can significantly improve throughput, improve quality and reduce costs etc. Some applications of these methods and benefits are detailed as follows.

In other configurations, users can configure the fluid delivery and orifice size distribution(s) and/or profile(s) to achieve substantially non-uniform distribution(s) and profile(s) to achieve particular transverse or axial distribution(s) and/or profile(s) of fluid composition and transformation times etc.

13.3.3 Evaporation Residence Time

Users preferably configure the direct fluid contactor 483 with desired or prescribed transverse distribution(s) and/or profile(s) of orifice size and spatial orifice density. These are variously configured to provide desired transverse distributions of orifice size with corresponding transverse distributions of drop size or micro-jet size 903 of the first fluid. E.g., by configuring fairly uniform transverse distributions of distributed orifices these form provide fairly uniform drops or micro-jets 903 with fairly narrow drop size distribution of a first fluid 901 in perforated tube arrays 260 in various embodiments of the invention. With continuing reference to Figure 18, Figure 19, and Figure 20 in other configurations, users configure desired transverse distribution(s) of orifice size, transverse distribution(s) of orifice spacing and transverse distribution(s) of orifice spatial density to achieve desired transverse evaporation time distributions, evaporation distance transverse distributions and transverse fluid delivery distribution(s).

Users consequently obtain evaporation time transverse distribution(s) for the fluid drops or micro-jets to evaporate within desired transverse distribution(s) of evaporation distance in flows of the second fluid 904 with various transverse distributions of unsaturated fluids. Similarly, users may form micro-jets from fairly uniform transverse distributions of orifice size with fairly uniform transverse distribution(s) of differential ejection pressure across the orifices 80, resulting in fairly narrow transverse distribution(s) of a measure of drop size such as the Sauter Mean Diameter (SMD). Consequently, these form narrower transverse distribution(s) of evaporation time and more controlled transverse distribution(s) of evaporation distance.

Since the time to evaporate drops strongly depends on the largest drops in a spray, users significantly reduce the portions of large drops in the spatial and number fluid delivery distribution(s) and/or profile(s). Accordingly they significantly reduce the size and cost of the evaporation equipment. William Sirignano (1999) reviews droplet evaporation rates including transient effects due to changing temperature in combustion, and the effects of neighboring drops in sprays or drop arrays. Davis & Schweiger (2002) further review the evaporation of drops. The vapor pressure of the first fluid 904 and the diffusion coefficient in turn depend on the effective temperatures of both the liquid and gas. The evaporation rate of a drop is generally proportional to its surface area, the difference between local and remote vapor pressures and a diffusion coefficient. Users utilize such methods in evaluating and configuring the parameters described herein.

To ensure substantially complete evaporation, users control the drop size or size distribution and residence time sufficient to generally limit the maximum evaporation time with a suitable statistical probability.

Accordingly, users create orifices with about the desired diameter distribution and/or profile and prescribed uniformity, adjust tube oscillation frequency, control the pressure pulsation pattern of the first fluid 901 and/or the external electric field outside the orifice, and the temperature of the two fluids and vapor pressure of the first liquid 901 in the second fluid 904 as appropriate, needed or desired. Then users select the area and length of the fluid duct 130, and the velocity (or pressure drop) of the second fluid 904 in a prescribed manner to control the first fluid residence time for evaporation. This similarly applies to using direct

contactor arrays 260 to evaporate the first fluid 901.

13.3.4 Heat Exchanger Residence Time

Drops (or bubbles) of a first fluid 901 traveling in a second fluid 904 change in temperature with evaporation, condensation and/or heat transfer and time. To achieve a given proportional change in temperature compared to the total temperature difference, users preferably configure a direct fluid contactor 483 of Figure 82 to incorporate numerous orifices with desired orifice area and spatial distributions and/or profiles to create and distribute fairly uniform drops or a narrow drop size distribution of the first fluid 901. By controlling those distributions and/or profiles together relative to the velocity distributions and/or profiles of the second fluid 904, users further provide prescribed spatial and number residence time distributions for the droplets of the first fluid 901 in the second fluid 904 in some configurations. By controlling those residence time distributions, users preferably control the spatial and number size distributions and fluid fraction distributions of the first fluid 901 that exits the fluid duct 130.

13.3.5 Condensation Residence Time

Cooler drops of a first fluid 901 contacting a second fluid 904 saturated with some vapor of a fluid will cool the second fluid 904 and condense some of that vapor. In some embodiments, users preferably configure the direct fluid contactor system 483 as a direct contact condensor 484. They preferably configure distributed contactor arrays 260 to distribute a cooler first fluid 901 in a second fluid 904 with desired transverse delivery distributions and/or profiles. The temperature of the first fluid 901 is preferably kept below a generally prescribed temperature. The contactor array 260 is configured with transverse orifice size distributions and/or profiles to achieve desired transverse drop size spatial and number distributions and/or profiles. E.g., in some configurations, these may be fairly uniform drops of the first fluid 901 or drops with a narrow size distribution.

They may further distribute those drops or with one or more desired transverse delivery distributions and/or profiles to achieve desired transverse profile ratios of the second fluid 904 to first fluid 901. E.g., These can be configured for fairly uniform ratios of the second to first fluids where there are distinctly non-uniform transverse flow distributions and/or profiles of the second fluid 904 in the fluid duct 130. The contactor array 260 is

commonly positioned across and within the fluid duct 130. The contactor 260 may also be arrayed near the upstream end, or across the inlet 134 to the fluid duct 130.

Users preferably provide a residence time distributions and/or profiles for the coolant fluid generally sufficient to achieve a desired or prescribed distributions and/or profiles of the fraction of the desired total temperature change. This achieves a certain amount of cooling of the second fluid 904 by the first fluid 901. This in turn will generally condense a certain fraction of the vapor in the second fluid 904. By controlling the uniformity or narrowness of drop size distributions, and the ratio profile of the distributions of first fluid 901 to the distributions of the second fluid 904 transversely across the fluid duct 130, (and/or axially) and the distributions in the difference in temperature between the first fluid 901 and the second fluid 904, users generally achieve a given condensation fraction.

13.4 Counter-Flow Direct Contact Heat Exchanger

Exhausting hot products of combustion to the atmosphere results in significant energy losses. Surface heat exchangers are typically used to recover such exhausted energy. Using sprays with a wide distribution of drops results in a portion of the smallest droplets being entrained in the exhaust plume with consequent loss of water.

With reference to Figure 83, to prevent or mitigate this droplet entrainment, users preferably configure a direct fluid contactor 483 as a heat exchanger to counter-flow drops of cold first fluid 901 against the hot second fluid 904 comprising one or more of a heated oxidant fluid, energetic fluid, and expanded fluid. They use distributed fluid contactor embodiments 10 or 260 to distribute fairly uniform drops of fairly uniformly across the second fluid or with desired transverse size distributions and/or profiles and transverse orifice spatial density distributions and/or profile(s). More preferably, they distribute the cooling first fluid 901 having a narrow drop size distribution with a flow distribution and/or profile across the duct 130 corresponding to the relative enthalpy flow transverse distributions of the incoming hot second fluid 904. I.e. taking the velocity distribution times the density distribution times the temperature difference above a reference temperature such as the cooling temperature to arrive at a relative enthalpy flow distribution.

Users preferably configure a generally vertical duct 130. They preferably select a mean drop size or narrow size distribution and design the transverse inlet fluid velocity

distributions so that the drops of cooling first fluid 901 fall through the counter flowing fluid. I.e. most coolant fluid drops 901 are formed larger and heavier than those that are entrained by the cooled fluid flow 928 exiting the duct. The force of gravity on the drops is greater than the sum of the hot fluid drag on the coolant drops and the buoyancy of drops in the counter flowing hot fluid. Conventional sprays generate "drafting" or coordinated drop motion. This increases drop entrainment. With distributed drop contactors, users preferably adjust drop velocity to compensate for the small drafting component.

As the drops fall through the counter flow of hot flue gas 904, they cool the flue gas. The hot gas in turn heats the drops. As a result, users recover hot liquid drops at the fluid collector 481 at the bottom of the flue 130, and deliver cold flue gas exiting the top 136 of the flue duct 130.

In some embodiments, users provide a particle separator 520 (e.g., gas-liquid separator) to separate the hot water near the bottom of the flue duct 130 from the hot flue gas 926 (See Fig. 83). The separator 520 may be conveniently formed using a separator 520 comprising series of turning vanes that direct the second fluid flow 904 upwards. At the same time, the separator 520 permits the heated diluent and condensed vapor or condensate to fall through the separator do the fluid collector 481. The heated coolant fluid 901 is collected in the collector 481 at the bottom of the flue 130. It is then preferably cooled, a portion is preferably recycled and portion of the condensate is recovered. The cooling fluid is preferably the same fluid as the vapor being condensed. By this counter-flow direct contact heat exchanger, 483 or 494, users desirably achieve an efficient and inexpensive recovery of the heat in flue gas exhaust stream. Users configure similar processes to recover heat in an hot exhaust fluid stream in some configurations. E.g., in the case of an exothermic reaction or where the fluids are otherwise heated.

13.4.1 Direct Contact Fluid Condensor

Further referring to Figure 83, when there is a condensable vapor in a hot second fluid 904 (e.g., steam or hot water vapor, or flue gas), the cold drops will condense that vapor and become hotter. In some embodiments, users preferably configure the direct contact heat exchanger 483 as a direct contact condensor to use the same liquid 901 as the vapor being condensed e.g., cold water to condense steam. Small drops provide a very high surface area

giving rapid heat transfer. This process of using a direct contact condensor advantageously provides an efficient means of recovering the first liquid fluid 901 from the second hot fluid stream 904.

In other embodiments, users use a preferably fairly inert liquid as the liquid coolant first fluid 904.For example users can use a low vapor oil such as is used in vacuum pumps, or a synthetic fluid or refrigerant. In modified embodiments users efficaciously use a liquid metal such as gallium which has a low vapor pressure and a very wide liquid range, as needed or desired.

Further referring to Figure 82, users preferably provide a spray cleaning system 498 to delivery a high intensity and volume spray to flush out accumulated particulates and wash the fluid contactor system periodically or as needed or desired. They correspondingly preferably provide a controller 590 to control the delivery of contacting fluid and contacted gas, and of the spray cleaning system 498. The cleaning system may move across the front of the ducts 131, or along them to clean the ducts as needed or desired.

13.5 Cross-Flow Contactor In some embodiments, users configure the direct fluid contactor heat exchanger as a cross-flow contactor.

13.5.1 Cross-Flow

Further referring to Figure 82, users preferably increase the effective surface contact area of drops by reducing the size distribution of orifices 80 and thus the spatial and number size distributions and/or profiles of drops delivered while increasing the number of orifices 80 and increasing the mixing and improving the transverse fluid distributions and/or profiles. However, the drop terminal velocity decreases with drop size. With counter-flow configurations, the maximum fluid velocity exiting the fluid duct 130 is preferably configured lower than the coolant liquid drops' terminal velocity to prevent drops from being entrained by the fluid exiting the duct at the outlet 134 and lost. Consequently the cross-sectional area of the duct is preferably increased as the drop size decreases i.e. so that the fluid velocity decreases. Conventional systems disadvantageously result in a wide range of drop size. This undesirably requires the fluid flow and duct area to be sized for the smallest size for the tolerable droplet loss rate in the exit fluid stream.

Users preferably generate fairly uniformly sized drops or drops with a desired narrow

spatial and number size distributions in transverse or axial directions with embodiments of distributed contactors 260. Users thus preferably increase the first fluid flow 901 and reduce the duct size while still achieving a very high droplet recovery. Even when users provide fairly uniform orifices 80 to obtain smaller more uniform droplets, there will typically be a bimodal distribution of drop size with narrow peaks. The users preferably size orifices or transverse orifice size distributions for a prescribed fraction of droplets recovered. Similarly users use a range of orifices in some configurations to increase turn down range. This provides narrower range of drop sizes than conventional spray systems. Again users preferably determine the desired fluid flow velocity distribution and size the ducts 130 accordingly to achieve the desired droplet recovery.

13.5.2 Multiple Horizontal plates

With reference to Figure 82, to overcome various limitations of residence times and velocity distributions, users preferably configure the direct fluid heat exchanger/contactor 483 to direct the inlet flow of the second fluid along the second flow path 4 through multiple thin sub-ducts 131 configured within the larger fluid duct 130. These can be formed by forming multiple duct walls 132 within the larger fluid duct 130. In some embodiments, users preferably orient these sub-ducts 131 and intermediate duct walls 132 somewhat horizontally, and more preferably tending downwards towards the exit, within the larger duct 130. Users then configure a direct contactor array 260 wherein they direct the fluid orifices 80 generally horizontally and upstream toward the inlet 134 near the inlet and upper portion of each horizontal thin sub-duct 131.

Users preferably use fairly uniformly sized orifices or with a narrow desired size distribution to form fairly uniform drops or micro-jets to give fairly uniform drop velocities and residence times. Similarly users form micro-jets forming a fairly narrow drop size distribution and which are fairly uniformly configured transversely across the sub-duct 130 to provide fairly narrow distributions in drop velocities and transverse spatial drop distributions and/or profiles. The orifice size, spacing and differential delivery pressure are preferably configured so that adjacent micro-jets overlap. Users preferably size the duct height relative to the second fluid flow velocity so that the fluid flow is generally laminar within the thin sub-ducts 131.

Fluid Residence Times: With further reference to Figure 82, users preferably size the vertical depth of the thin ducts 131 together with their length and width relative to the inlet design fluid flow velocity and contacting fluid drop size distribution so that the contacting liquid drops traverse the thin duct 131 and contact the lower surface of the thin duct 131 in desirably less time than the residence time of the fluid within the duct. Users then preferably control the fluid flow rate and the drop delivery rate relative to the fluid flow distribution so that a desired fraction of the fluid has a fluid residence time greater than the time for a desired fraction of the drops to fall from the top to the bottom of the thin horizontal ducts.

Spray flushing: Users preferably configure the spray cleaning system 498 to clean each thin duct and periodically flush and wash out the accumulated particulates. Users preferably provide numerous spray orifices along the contactor tube 80 for the first fluid 901 with a high pressure delivery pump to provide a flushing spray across the full width of the sub-duct 131. In other embodiments, users provide a moveable spray cleaning system 498 that periodically moves across the sub-ducts 131 and sprays each sub-duct in turn. In modified embodiments, users use a narrow high pressure spray system to sequentially traverse across each sub-duct to clean it.

Duct Angle: To reduce the tendency for the contacting fluid such as water to stand in the sub-duct, with further reference to Figure 82, users preferably tilt the cross-flow duct 130 and sub-ducts 131 to a predetermined or pre-selected angle, preferably downhill towards the duct exit 136. This enhances the contacting liquid flow down the duct 130 in the direction of the inlet fluid flow, preferably carrying recovered particulates with it. When users spray clean each sub-duct 131, this preferable tilt similarly assists in flushing the duct 131 and removing the accumulated particulates. This configuration reduces liquid waves and duct blockage relative to other configurations.

To further assist the fluid flow, users preferably tilt the sub-ducts 131 downwards transverse to the fluid flow 904. This assists in flowing the fluid 901 to one downstream corner of the fluid duct 130. Users provide a collector duct 481 to collect the fluid 901 flowing out the sub-ducts 131.

In other embodiments, users further tilt the sub-ducts downwards towards the upstream direction so that the resulting collected contacting liquid at the bottom of the duct

flows counter flow to the fluid flow towards the duct inlet 134.

Sizing: Users preferably size and configure the number of sub-ducts 131 and their width and length to reduce net present value of the life cycle costs of the fluid contactor system. (See Figure 82.) These include pumping power needed to deliver or exhaust the contacted fluid, pump and recirculate the contacting fluid or liquid, the cost of spray cleaning the system 498, and of the cleaning operations.

13.5.3 Direct Contact Co-Flow Heat Exchanger

In some embodiments, with further reference to Figure 82, users configure the direct fluid contactor system 483 to distribute droplets of the first fluid 901 that are entrained into the co-flowing second fluid 904 or are injected in the direction of fluid flow. This configuration will form in a direct contact co-flow heat exchanger 483. It is useful or particularly significant where the second fluid is saturated with the first fluid, or where the first fluid has a low volatility.

In embodiments where users desire or need to recover the first fluid, various liquid retrieval methods may be used, such as electrostatic precipitators, cyclones, impingement separators, etc. The fairly uniform size drops used will result in much greater recovery of the injected liquid.

13.6 Fluid Scrubber In other embodiments, users configure the direct fluid contactor 483 as a fluid scrubber to remove various contaminants, such as shown in Figure 82.

13.6.1 Intake Water Scrubber

Intake air or compressed oxidant containing fluid is commonly filtered through a porous intake filter to remove particulates. This reduces the compressor 407 and turbine fouling thus preventing efficiency losses at the expense of a pressure drop with consequent pumping losses. By using a multi-duct direct contactor 483, users achieve both wet scrubbing to remove particulates and fibers from the intake air, as well as cooling the intake second fluid 904. (See, e.g., Figure 82.)

13.6.2 Exhaust Water Scrubber

Users similarly configure a direct fluid contactor 483 with numerous in a desired size distribution to scrub the exhaust fluids from combustion or power generation system. (See,

e.g., Figure 82). By controlling the profile of the ratio of the spatial flow distribution of scrubber contacting first fluid 901 to the flow distribution of the second fluid 904 being scrubbed, users desirably achieve a more effective scrubbing action.

13.6.3 Solution Scrubber

With further reference to Figure 82, users similarly extend this scrubbing method to using solutions instead of clean water first fluid 901. Caustic solutions first fluid 901 are commonly used to scrub flue gases 926 from acidic emissions. By reducing drop size and increasing the direct contact drop surface, users significantly improve the scrubbing rate of such acidic and other emissions from a fluid stream.

13.7 Direct Contact Thermal Fluid Control With reference to Figure 82, in other embodiments, users utilize the perforated tube arrays 260 to heat or cool second fluids 904 by direct fluid contact with a first fluid 901 by forming a direct contact fluid heat exchanger 483. Users can use the sensible heat of changing the temperature of the injected first fluid 901, and/or the latent heat from evaporation of an injected first fluid liquid 901. They may similarly use the multi-duct horizontal configuration of the direct contact heat exchanger as shown in Figure 82.

13.7.1 Cooling by Cold or Refrigerated liquid

With reference to Figure 82, to cool a fluid, users configure the direct contact heat exchanger 483 in a vertical configuration to preferably distribute cool or refrigerated liquid first fluid 901 through the distributed contactor arrays 260 to provide a very high surface area direct contact heat exchanger 483. This provides faster and more efficient heat transfer than the relevant art. For maximum effect, users preferably cool or refrigerate the water in the range of 0.1 °C to 4 °C, and preferably to about 2 °C. Users then take this cold water first fluid 901 and contact the oxidant fluid 904 (e.g., air) with one or more distributed contactor arrays 260. This enables efficient cooling of the oxidant fluid 904 (e.g., intake air) without large amounts of evaporation of the first fluid 901 as in conventional “fogging” systems.

With reference to Figure 82, users further use the direct fluid contactor system 2 to preferably cool the intake air to a energy conversion system as needed or desired. E.g., when users wish to increase the fluid density and the pumping capacity of a compressor 407. By using a direct fluid contactor system 483, users preferably achieve more uniform transverse

fluid distribution between the diluent first fluid 901 and the oxidant fluid 904, thus achieving more desirable or uniform spatial ratio profiles of diluent to oxidant. Advantageously, this improves the compressor efficiency, and the temperature uniformity of the downstream combustor. In turn, this enables users to increase the fuel flow rate and system power and efficiency.

13.8 Distributed Direct Contact Fluid Heater

With reference to Figure 82, in situations where users wish to heat fluids, users preferably dispose a perforated tube array 260 across the duct containing a second cool fluid duct to form a direct contact heat exchanger 483. Users then deliver a hot first fluid through the perforated tube array 260. With fairly uniform orifices, users form fairly uniform fluid jets or drops with desired spatial flow distributions and/or profile resulting an a very high direct contact surface area with a desired ratio of contactor first fluid 901 to contacted second fluid 904.

13.8.1 Low Vapor Pressure Liquid

When users wish to heat a cool fluid without vaporizing a significant portion of the hot first fluid, users preferably use a liquid with a very low vapor pressure. High molecular weight hydrocarbons such as vacuum pump oil may be used for moderate temperatures up to a few hundred degrees C. For higher temperatures, users preferably use the liquid metal gallium which has a very low vapor pressure and a very wide liquid temperature range.

13.8.2 High Vapor Pressure Liquid

With reference to Figure 82, in cold climates, it is preferable to both heat and humidify oxidant second fluid 904 or air when heating it. In using a diluent liquid first fluid 901 such as water that has a significant vapor pressure, a substantial portion will evaporate as it traverses the second fluid 904, humidifying the air. Users preferably distribute hot water though a perforated tube array 260 configured across the air duct. By providing fairly uniform orifice and drop sizes or micro-jet sizes, users achieve a more compact direct contact heat exchanger 483 with higher heat transfer rates.

Where heating is associated with a demand for power, users preferably use a direct contact heat exchanger 483 as a direct contact condensor to cool the exhaust fluid 926 and condense the thermal diluent first fluid vapor 901 (e.g., steam and water vapor) while

recovering high purity hot thermal diluent first fluid 901 (e.g., hot water). Users then pass that high purity hot water through a liquid - liquid surface heat exchanger 470 to preheat common water. Users preferably recycle the high purity cooled water first fluid 901. Users take the heated common water and use it for district heating applications.

13.8.3 Hot Contact Liquid Recovery

With reference to Figure 82, when delivering a hot liquid, users preferably provide a direct contact heat exchanger 483 in a counter flow configuration such that the fairly uniform hot liquid drops of the first fluid are delivered through the cool second fluid. E.g., a thermal diluent first fluid 901 through an oxidant fluid 904. The hot first fluid drops cool while they heat the second fluid. As before, users preferably adjust the drop size and fluid velocity so that the fairly uniform hot liquid drops traverse the cool second fluid. Alternatively users can utilize the cross-flow or co-flow contactors described above with reference to Figure 82. With high vapor pressure liquids, users preferably account for the evaporation and change in drop size when sizing the direct contact heat exchanger 483 and configuring the fluid velocities for a desired residence time distribution, and selecting the spatial distribution of orifices and drop formation or micro-jet size and distribution.

14 DISTRIBUTED LIQUID EVAPORATOR In some embodiments, with further reference to Figure 82, users configure one or more direct contactors 10 or contactor arrays 260 to deliver a first liquid within the fluid duct 130 with one or more desired fluid delivery spatial distributions relative to the mass flow distribution of a second fluid within that duct to evaporate the first liquid 901 within the second fluid 904 to a desired degree.

For example, the direct contactor 2 may be configured to preferably form direct contactors to deliver a first fluid 901 through numerous orifices 80 with a desired distribution within a combustor. In such an embodiment, the first fluid 901 may be gaseous or liquid fuel, such as natural gas or diesel fuel, or a thermal diluent fluid such as steam or water. Users preferably select combinations of one or more orifice diameters, number of orifices, orifice configurations, orifice distributions, differential fluid pressure, fluid temperature and electric field magnitude and gradient to achieve the desired or needed delivery drop size and distribution as described herein. Users correspondingly select the thickness and diameter of

the tube wall and/or orifice forming technology with suitable Thickness/Diameter capabilities to cost effectively form the number of orifices 80 with the desired parameters. In some configurations, they provide protective coatings to protect against high thermal fluxes, erosion, oxidation and corrosion.

14.2 Narrow Size & Residence Time Distributions

Fairly large distributions in drop size cause corresponding differences in evaporation time with the residence time having to be selected for the longest evaporation times caused by the largest drops. To improve evaporation times of the first liquid 901 within the second fluid 904 within prescribed dimensions of a fluid duct 130, users preferably position a distributed contactor array 260 with a desired size distribution of orifices 80, in one or both directions transverse to the axis of the fluid duct 130 containing the second fluid 904 with further reference to Figure 82. They similarly preferably control the differential fluid pressure across the orifices 80 and thus control the spatial distribution of drop formation or micro-jet formation and corresponding fluid flow distributions. Accordingly, they provide one or more desired spatial (and number) distributions and/or profiles of drop sizes or spatial profiles of fairly narrow drop size distribution across (and along) the duct 130.

14.2.1 Static or Uniform Flows & Evaporation Times & Distances

For example, referring to Figure 82, with where the second fluid 904 is fairly static or has a fairly uniform axial flow distribution across the fluid duct 130, or in a vacuum, users preferably form fairly uniform orifices 80 in the contactor array 260 across the duct 130 containing the second fluid 904. They thus generate fairly uniform drops of the first fluid 901 fairly uniformly distributed across the fluid flow 904 within the duct 130. Similarly they provide fairly uniform micro-jets with fairly uniform narrow drop size distributions across the duct 130.

These drops of the first liquid 901 evaporate within a fairly narrow range of time. In similar flow velocities, this narrow spatial distribution of residence times results in fairly narrow axial distribution of locations where the drops evaporate. The evaporation residence times and evaporation locations are broadened somewhat by turbulence within the flow. Users thus obtain a fairly narrow transverse spatial variation of the cumulative distribution of evaporation distances. Users preferably adjust the orifice size 80 and applied differential

ejection pressure to adjust the drop size to obtain the desired cumulative probability of evaporation and/or cumulative probability of drop size at a desired distance from the contactor array 260.

Similarly, with higher differential ejection pressures, users provide numerous larger micro-jets along the contactor array 260. They achieve a fairly narrow size distribution of drops with a fairly narrow distribution of evaporation residence times.

14.3 Orifice size profiles, evaporation time & distance distributions

In other configurations, with reference to Figure 19, the second fluid 904 exhibits substantial variations in one or more transverse distributions of axial velocities within the fluid duct 130. For example, with laminar flows, the flow exhibits highly parabolic profile while with highly developed turbulent flows, the flow distribution is much flatter in the center with rapid declines in the boundary layers near the walls. In such configurations, users preferably adjust the orifice size distribution and differential ejection pressure to achieve a drop size distribution where the evaporation time varies approximately inversely with the fluid velocity distribution such that the transverse distribution of axial evaporation distances is about the same across the duct in at least one or preferably both transverse directions. E.g., users preferably form smaller orifices 80 and drops near the center where the velocity is the greatest to provide shorter evaporation times compared with larger orifices near the wall with longer evaporation times to compensate for the varying transit times to achieve fairly uniform evaporation distances.

14.4 Transverse Flow Distribution Profiles & Ratios

With further reference to Figure 18, Figure 19, and Figure 20, in some configurations users seek to control the transverse mass delivery spatial distributions and/or profiles of the first fluid 901 relative to the transverse mass flow distributions and/or profiles of the second fluid 904. They preferably adjust the spatial density of orifices 80 in the contactor array 260 together with the transverse distribution of orifice sizes and orifice flow factors (cross-sectional area of the liquid jet as it exits the orifice to total orifice discharge cross-sectional area) to achieve a desired transverse spatial net specific discharge area of orifices 80 per cross-sectional area of the fluid duct 130. They correspondingly adjust the differential ejection pressure across the tube wall 30 and account for the longitudinal distribution of the

differential ejection pressure along the tube 10 to achieve a desired transverse fluid flow distribution through the tube.

Users similarly adjust the transverse fluid flow distributions and/or profiles of the first fluid 901 relative to the fluid flow distributions and/or profile of the second fluid 904 accounting for the tube to tube gap distribution and upstream to downstream spatial distribution of pressure drop across the contactor array 260 to achieve the desired ratio of mass flow distributions (or profiles) of first fluid 901 relative to the mass flow distributions (or profiles) of the second fluid 904. Accordingly, users preferably control the spatial transverse and axial flow distributions and/or profiles of the first fluid 901 relative to the transverse flow profiles of the second fluid 904 to achieve desired spatial transverse and axial flow profile ratios of the second fluid to first fluid.

14.5 Distributed Evaporator or Cooler Users preferably use embodiments of distributed contactor arrays where users wish to evaporate a first liquid (e.g., water) to cool and/or increase that vapor concentration in a second fluid. E.g., evaporate water to cool or humidify air. Water is being introduced to cool intake air in power generation systems to increase power and reduce NO_x emissions. Users preferably use distributed contactor arrays, as described herein, in such applications to provide substantial benefits over prior art. Some embodiments are detailed as examples of these applications as follows.

14.6 Quasi-isothermal compression

As schematically shown in Figure 84, in some embodiments, users provide one or more direct contactor arrays to deliver a thermal diluent first fluid 901 into a power conversion system utilizing a second fluid 904 (such as an oxidant containing fluid such as air or oxygen enriched air.) This may be accomplished through a direct contactor configured as a distributed contactor precooler 404 that provides an "overspray" of vaporizable thermal diluent into the intake of a first compressor 407. Similarly, users may configure an direct contactor as an intercooler 410 between two compressors 407. A further contactor may be provided as an aftercooler 417 after the compressor and before the combustor 424. Contactor tubes may further be configured within the compressor to progressively distribute thermal diluent within the compressor. Similarly a distributed contactor may be configured within the combustor 424.

This thermal diluent 901 is preferably a vaporizable liquid (such as water) to provide evaporative cooling of the second fluid 904 when mixing the diluent. The latent heat of vaporization of the vaporizable first fluid 901 absorbs heat, reducing the temperature of both the second fluid 904 and the first fluid 901. This in turn beneficially reduces the net work of compressing that second fluid.

As shown in Figure 35, Figure 36 and Figure 37 users preferably streamline the perforated tubes 10 to reduce the pumping work of delivering the second fluid through the contactor array 260. In some configurations, users preferably use heated vaporizable fluid 901 and deliver it under pressure so that vapor bubbles nucleate within the droplets to rapidly shatter the drop into smaller droplets ("flashes") on delivery. These droplets evaporate faster and within shorter distances than conventional methods. They further provide means to recover heat in the hot fluid exhausted from the expander 440 and recycle it.

For example, users preferably spray water as the first fluid 901 into the flow of an oxygen containing second fluid 904 such as air, after, between, within or before the compressor(s) 407 to evaporatively cool the gaseous fluid 904 being compressed and reduce the work of raising the pressure of the second fluid 904. They preferably configure the spatial orifice spatial density distributions and profiles and/or spatial orifice area profile to provide prescribed or desired profile ratios of the transverse delivery profiles of the second fluid to the first fluid e.g. in transverse and/or axial directions. By adjusting these ratios users beneficially achieve more controlled fluid composition and temperature than in relevant art methods.

In some configurations users configure the precooler to deliver non-uniform distributions of the first fluid to accommodate the centripetal motion of droplets and their evaporation patterns within the compressor. These may be weighted more towards the compressor radius than in conventional methods. In other configurations, users provide more uniform transverse fluid compositions and temperatures than are obtained in the relevant art.

14.6.1 Inter-Compressor Diluent Drop Delivery

With continuing reference to Figure 84, in some configurations where multiple compressors 407 are used to achieve a desired pressure, users cool the compressed second fluid 904 between the compressors 407 by configuring a distributed contactor array as an

inter-cooler 410 to efficiently deliver the vaporizable cooling first fluid 901 into the compressed second fluid 904, in some embodiments. Depending on the velocity profiles, temperature profiles and humidity profiles of the compressed fluid 904 at that location, users preferably configure one or more of the pressure and/or temperature of the coolant fluid 901, the spatial (e.g., transverse) distribution(s) of orifice sizes, the transverse distribution(s) of net orifice specific spatial density (net orifice area per duct cross sectional area) to achieve desired transverse distribution(s) of first fluid mass delivery rate. These are configured to achieve the desired spatial (e.g., transverse) profile(s) of relative fluid flow rates and desired spatial (e.g., transverse) profiles of the relative fluid composition or ratio of the second fluid to the first fluid (or vice versa).

They preferably configure one (or both) spatial or transverse spatial distributions of orifice area and the profile ratio of second to first fluid flows, to desirably provide one or more spatial or transverse profile(s) of the rate of liquid evaporation, transverse profile(s) of the droplet evaporation residence time, and spatial (e.g. transverse) distribution(s) and/or profile(s) of the evaporation distance. For example, Figure 18 exhibits a conceptual transverse velocity flow profile of a second fluid from inner radius to outer radius of an annular duct. This is shown as a multi-parametric transverse distribution similar to a skewed inverted parabolic distribution. There are similar transverse distributions for the temperature and pressure of the second fluid (not shown). These parameters are used to evaluate the corresponding transverse distributions of mass flow of the second fluid (not shown).

Users preferably desire evaporation distance spatial distribution(s) or profile(s) for the vaporizable diluent. E.g., to provide desired composition, or temperature distributions or profiles, and/or to reduce impact erosion from large drops. A conceptual evaporation distance transverse distribution is shown in Figure 19 as a nonlinear transverse distribution similar to a shallow parabolic curve.

From the desired evaporation distance transverse distribution(s) and the second fluid boundary conditions, users preferably evaluate the available transverse distribution of the allowable maximum residence time or maximum evaporation for the first fluid. This maximum evaporation time transverse distribution is shown schematically in Figure 19 as the solid curve with high evaporation times near the inner and outer radius of the annular duct

and low residence times near the middle of the duct.

E.g., these calculations incorporate the spatial (e.g. transverse) velocity distributions or profiles of the two fluids, their temperature and pressure distributions or profiles, the relative saturation pressure distributions, diluent vapor pressure distributions, and drag distributions on the diluent drops. From the desired evaporation time and the relevant parameters, users obtain the desired spatial (e.g., transverse) distributions of measures of the first fluid drop size such as the Sauter Mean Diameter (SMD) or similar measures of drop size number distribution.

Users similarly evaluate the ratio of transverse fluid mass flow profile(s) desired to obtain desired transverse composition or ratio profile(s). E.g., they take the second fluid spatial or transverse flow velocity, pressure and temperature distributions and/or profiles to evaluate the desired spatial or transverse density and mass flow distributions. From these, they evaluate the desired first fluid spatial or transverse mass flow distribution(s) needed to achieve the desired spatial or transverse composition ratio profile(s).

Combining the desired spatial or transverse drop size profile(s) (as needed to achieve the evaporation distance distribution), with the desired first fluid spatial flow distribution(s) (to achieve the composition distribution(s) or flow ratio profile(s), users preferably solve the relevant simultaneous equations obtain the desired spatial or transverse orifice spacing distribution(s) (or the inverse lineal orifice density), and the spatial or transverse net orifice spatial density distribution(s) (per duct cross section area).

From the orifice size and first fluid flow rates, users obtain the desired jet penetration spatial distributions or profiles and the spatial differential ejection pressure distributions required to achieve those flows, and the desired tube gap distributions. Where there are constraints among these parameters, users adjust some of the parameters to achieve other parameters within desired ranges. E.g., by adjusting tradeoffs in evaporation distance, tube size and tube gaps and their spatial distributions.

In a similar embodiment, users select the desired tube to tube gap size distribution. E.g., as a increasing gap between two radial direct contactor "spokes", or as a uniform spacing between two circumferential direct contactor arcs. Users preferably select a desired spray penetration distance relative to these tube to tube gaps to provide a more uniform

transverse distribution of the second to first fluids across the tube to tube gap, downstream of the contactor array. E.g., equal to about 90% of the tube to tube gap at the design conditions. The transverse distribution of tube gap and jet penetration are conceptually shown from the inner radius to the outer radius in Figure 18.

From the constraints of the transverse distribution of the jet penetration distance (eg as a function of the tube to tube gap distribution), and the transverse distribution of the first fluid drop size measure (e.g., SMD), they calculate the required fluid delivery pressure required to achieve the transverse distribution of differential ejection pressures and the transverse distribution(s) of orifice size required to achieve those drop sizes and penetration distances.

With these parameters, users further constrain the local desired transverse distribution of composition or second fluid to first fluid flow ratio profiles. From these constraints and parameters, they calculate the orifice spacing or lineal density, and the net orifice spatial density required to achieve the first fluid flows to give the desired local transverse distribution of fluid composition or second fluid to first fluid flows.

In performing these calculations, users preferably account for the pressure drops along the contactor tubes as well as the friction losses and pressure drops for the flows through the orifices. The pressure drops through orifices are particularly significant for higher orifice thickness to diameter ratios resulting from small orifices and thick tube walls, and for long contactor tubes relative to the tube hydraulic diameter. For example, as shown in Figure 20, with small tube diameters relative to the contactor tube length, the pressure of the first fluid along the first flow path pressure drop inside the contactor tube may drop very substantially. The pressure drop can be markedly non-uniform as a result of the longitudinal distributions of orifice size and spacing along the contactor tube. These variations in fluid flow and pressure within the tube are preferably accounted for in configuring the desired transverse parameters.

Figure 20 shows schematically the resulting transverse distribution of orifice diameter from inner to outer radius of an annular duct to meet the desired constraints for one embodiment. The transverse distribution of the orifice to orifice spacing from inner to outer radius is similarly shown. Note that sprays are specifically allowed to overlap or move apart

to achieve this variation in orifice spacing. Figure 20 further shows the highly nonlinear variation in the first fluid pressure transversely along the contactor tube with small contactor tube hydraulic diameters relative to the contactor tube length. The consequent highly non-linear first fluid flow per orifice is further shown in Figure 20 as an skewed inverted parabolic type transverse distribution.

These substantially non-linear transverse distributions of orifice size, orifice spacing, pressure and mass flow per orifice are required to achieve the uniform transverse ratio profile of second fluid to first fluid shown in Figure 20, given the constraints on the transverse evaporation distance, transverse distribution of jet gap penetration, and the local average ratio of second to first fluid mass flow in the first transverse directions as shown in Figure 18, Figure 19 and Figure 20. Correspondingly, these parameters can similarly be configured to achieve other substantially non-uniform transverse ratio profiles of second to first fluid flows.

In a similar fashion, the constraints and parameters can be evaluated the corresponding transverse distributions of orifice size, effective net orifice spatial density (including orifice spacing and tube to tube gap) and fluid delivery pressures. These can be configured as before to achieve the desired transverse distributions of evaporation distance, jet penetration, and locally averaged composition or second to first fluid flow ratio profiles, whether uniform or non-uniform as desired.

14.6.2 Post-cooler Compressor Diluent Drop Delivery

In some embodiments or power systems, users preferably provide embodiments of distributed contactors as a post-cooler 417 to introduce the first fluid 901 thermal diluent (e.g., water) into the compressed second oxidant containing fluid 904 after the sequence of one or more compressors 407 and before the downstream utilization device such as a turbine 440. The evaporation after the compressor cools the compressed second fluid 904, reducing the back pressure on the compressor 407 (compared to adding a non-evaporating fluid). Evaporation after the compressors (407) further reduces the temperature and volume of the second fluid while increasing the total mass of the fluid flowing through the utilization device 440. These parameters reduce the work of the compressor compressing the second fluid 904 compared to systems without post diluent delivery and evaporative cooling.

The second fluid 904 exiting the compressor 407 commonly has spatial or transverse

flow velocity distributions or profiles that vary markedly from the mean flow. The transverse flow distributions or profiles exiting the high pressure compressor 407 often vary substantially from the transverse flow distributions or profiles exiting the low pressure compressor 407. Users preferably apply the methods described above in reference to Figure 18, Figure 19 and Figure 20 to arrive at one or both desired spatial or transverse distributions or profiles of the orifice area sizes to form transverse profiles of drop size distributions to achieve drop evaporations within desired spatial or transverse distributions of drop evaporation times. These transverse drop evaporation times are preferably configured relative to the spatial or transverse flow velocity distributions to achieve desired distributions of axial evaporation distances.

In doing so, they preferably account for the hotter temperature, higher pressure, increased diluent content and higher density of the second fluid 904, and more non-uniform transverse velocity distribution than within the compressor 407, resulting in faster evaporation and lower evaporation residence time than within or between compressors.

Where substantially non-uniform velocity distributions exist, users preferably adjust the spatial or transverse orifice size distributions relative to the velocity to achieve fairly uniform spatial distributions of drop evaporation distances. They further preferably configure the orifice spacing relative to gap spacing and velocity to configure one or more spatial or transverse distributions or profiles of net spatial orifice specific density and deliver the first fluid with flow distributions to achieve prescribed spatial or transverse profile ratios of the second fluid relative the first fluid flows.

In some embodiments, users preferably deliver the first fluid 901 through streamlined direct fluid contactor arrays 417 and mix it with the second fluid 904. For the same amount of evaporative cooling, water delivered and evaporated after the compressor 407 and before the turbine appears to give lower fluid pumping and turbo-machinery parasitic losses from turbulence, wall friction etc in the second fluid 904 by reducing the compressor back pressure than the same amount of water evaporated prior to or within compressors 407.

With continuing reference to Figure 19, in some configurations, these transverse distributions of drop evaporation distance are preferably configured uniformly across the fluid duct 130, such as were uniform fluid composition distributions and temperatures are

desired entering a downstream combustor. In other configurations, these axial evaporation distance transverse distributions are adjusted to conform to other spatial transverse distributions desired in delivering the oxidant fluid 904 into a downstream combustor.

Users preferably deliver the diluent water through distributed contactor arrays with numerous orifices forming small drop sizes of less than about 100 μm in diameter, preferably less than about 30 μm, and more preferably less than about 10 μm. Users preferably use streamlined water distribution contactors to reduce the pressure drop across the array. By more uniformly delivering the first fluid 901 (e.g., water) throughout the second fluid 904 with smaller drop size and greater surface area than conventionally, users reduce the energy and entropy loss required for mixing compared to conventional water spray systems. Such combinations provide significantly faster evaporation, smaller volume and pressure vessel cost, and lower pressure drop than relevant art systems. (E.g., compare Humidified Air Turbine (HAT®) or the Evaporated Gas Turbine (EvGT) power systems.)

14.6.3 Intra-Compressor Drop Delivery

In some configurations, users similarly preferably apply this distributed water delivery method to intra-compression to deliver a diluent liquid first fluid 901 into the second fluid 904 being compressed within a compressor 407. They preferably configure direct contactor tubes 10 to distribute vaporizable diluent from near the hub or along compressor vanes as direct contactor tubes 10 to deliver the vaporizable thermal diluent fluid 901 with a desired flow distribution relative to the flow of second fluid 904 being compressed, using the methods described herein. In some configurations, they further provide contactor tubes along the compressor blades. These may be further combined into the vane and blade shapes with orifices exiting the vane or blade surfaces. These measures provide the benefit of more uniformly cooling the compressed flow and reducing its volume (compared to using excess air as diluent) and thus reducing the compression work required compared to the relevant art.

14.6.4 Pre-compressor Drop Entrainment

With continued reference to Figure 84, users seek to provide water droplet entrainment (or "overspray") into the air flow 904 into the compressor intake duct, using a precompressor distributed fluid contactor 404 with numerous orifices distributed across the fluid duct at or near the entrance of the compressor 407. Users preferably configure

streamlined contactor tubes to reduce the intake pressure loss at the duct inlet.

With numerous orifices in the streamlined fluid contactor 260 users provide numerous micro-jets. These achieve narrower spatial and number drop size distributions across the intake. Improving the spatial distributions and profiles of drop size resulting in a smaller fraction of large drops significantly reduces blade erosion within the compressor 407.

Users preferably configure the orifice net spatial density distributions and differential ejection pressure distributions to achieve one or both desired spatial profiles of the ratio the second fluid 904 to first fluid 901. These profiles are preferably configured to provide more uniform profiles of the second to first fluids (e.g., air to water.) Where users entrain vaporizable diluent into the compressor, they preferably provide fairly uniform spatial delivery distributions in proportion to the fairly uniform velocity distributions for the oxidant fluid entering the compressor 407. Users preferably utilize the methods of configuring the contactor array parameters as above, but with reference to the much more uniform velocity distributions, lower pressures and lower diluent content at the entrance to the low pressure compressor 407.

Improving these transverse distributions of fluid ratios significantly improves the uniformity of fluid cooling, fluid density and fluid velocity within the compressor 407. This reduces propensity for compressor surge and improves compressor efficiency compared to the relevant art, giving significant cost advantages. The improved evaporation and fluid ratio profile uniformity further improves downstream combustion temperature uniformity, combustion stability, and turbine efficiency.

Evaporation prior to compression results in an additional volume of water vapor that is compressed with corresponding parasitic flow losses. Providing distributed contactor arrays 260 to entrain or deliver fairly uniform water drops into the compressor(s) 407, between compressors 407 or after the compressor(s) is significantly more efficient than "fogging" before the compressor 407.

14.6.5 Cooling gas by "fogging"

Evaporative air cooling is being added to the air intake systems for power plants to cool the air, increase air density and mass flow into the energy conversion system, increasing its power, and to add thermal diluent to reduce nitrogen oxides formed by combustion.

Conventional systems create wide drop size distributions. Unevaporated drops impacting on blades can cause blade erosion. Wide drop size distributions require long residence times and distances to evaporate the largest drops or to let them fall out. This requires a large volume duct prior to the compressor 407.

In some embodiments, users provide distributed contactors with numerous orifices in the fluid duct upstream of the compressor 407. In some configurations they preferably form fairly uniform orifices to provide fairly uniform size transverse profiles of drop sizes or micro-jets with transverse size profiles of narrow drop size distributions.

With one or more of these measures, users configure desirable transverse distributions of drop evaporation residence times to evaporate the drops and correspondingly narrower spatial profiles of evaporation distances.

They further preferably configure a fairly uniform ratio of second to first fluid flow profiles. Where "fogging" is desired, users position the distributed contactor upstream of the compressor 407 sufficiently far to evaporate a desired fraction of the water drops prior to entrainment into the compressor 407.

Users may also position a multi-duct cooler 483 (as shown in Figure 82) before the compressor. This system can be used to spray cold water into the intake air to cool it without as much evaporation prior to the compressors. With one or more of these methods, users can reduce system size and cost compared to the prior art.

14.7 Counter Flow Evaporator

In some embodiments, users configure a direct fluid contactor 483 as a highly counter flow evaporator. The fluid duct 130 is preferably configured vertically. Users configure a direct contactor array 260 across the duct 130 near the top of the fluid duct 136. They size orifices 80 to form drops of the first fluid 901 generally of sufficient size and velocity so that they will fall or move against the second fluid flow 904. They typically provide a means of recovering the drops near the bottom or inlet 134 of the duct 130. Where fluid drops 901 are formed that are entrained with the second fluid flow 904, users preferably position the contactor array 260 a suitable distance below the top of the duct 136 so that the entrained drops 901 are evaporated to a desired degree before exiting the duct.

14.8 Hybrid Counter-Co Flow Evaporator

To more efficiently evaporate a liquid 901 in a fluid duct 130 with a vertical updraft flow, users preferably provide a direct contactor 260 across the duct 130 and form numerous drops or micro-jets with a fairly narrow size distribution to form a hybrid counter-co flow evaporator. Drops of fluid 901 below a critical size will be entrained by the vertical counter flow 904, while larger drops will initially fall as they evaporate. The contactor array 260 is preferably sized to form fairly uniform drops which will initially fall against the counter-flowing fluid 904.

Users preferably size the drops 901, height of the contactor array 260 above the inlet 134 to the evaporator, and velocity of the second fluid 904 such that when the drops have partially evaporated, the drag of the counter-flowing fluid 904 will then reverse the droplet velocity and entrain the drops 901 vertically upward along with the flow before the droplets fall to the bottom inlet 134 to the evaporator. This results in drops evaporating while they twice traverse the same region within the fluid duct 130. Consequently users have about twice as many drops within the fluid duct 130 for a given number and size of orifices 80 as compared with a co-flow configuration. This significantly increases the evaporation rate within a given duct 130, while permitting larger orifice sizes 80, thus reducing filtration requirements.

Users similarly configure the location of the contactor array 260 below the top (outlet) of the evaporator 136 sufficient to evaporate most of the droplets entrained vertically upward to a desired degree before exiting the evaporator. Users preferably size the size distribution of first fluid drops delivered relative to the second fluid flow so that a prescribed fraction of the drop mass will evaporate within the period when they are falling, entrained upward through the contactor array 260 and before they leave through the evaporator exit 136. (E.g., 99.97%.)

More preferably, users adjust the spatial orifice size distributions to achieve desired spatial distributions of evaporation residence times, and spatial distributions of evaporation distances as described herein. They further adjust the net spatial density distributions to achieve desired spatial profiles of the ratio of second fluid flow 904 to first fluid flow 901, and associated transverse evaporation time and distance distributions and spatial saturation distributions.

14.9 Co-flow Evaporator

In other configurations, to evaporate a first liquid 901 in a second fluid 904, users configure a co-flow evaporator system with a direct contactor array 260. Users preferably size orifices 80 to generate drops of sufficiently small size that the drops are entrained in the flow and carried away from the contactor array 260.

14.9.1 Upward Co-Flow Evaporator

When users have a temperature differential, users preferably orient the evaporator duct 130 in the vertical direction to benefit from natural updrafts. To achieve a highly co-flow configuration, users preferably size the orifices to form drops of the first fluid 901 that are sufficiently small to be generally entrained by the second fluid 904 against gravity. I.e. the drag on those drops is less than the force of gravity on them. Gravity reduces the velocity of the entrained drops 901 to less than the velocity of the second fluid 904. Such a vertical updraft configuration provides a desirably longer evaporation residence time and shorter length of the evaporator 130 than a downdraft configuration.

14.9.2 Downward Co-Flow Evaporator

In alternative embodiments, users configure a co-flow evaporator with a downward flow of the second fluid and corresponding downward flow of the first liquid drops. Here gravity accelerates the first liquid 901 as well as the flow of the second fluid 904 resulting in higher velocity and lower residence time than the hybrid counter-co flow and the upward co-flow configurations.

14.10 Radial Co-Flow Evaporator

Where a second fluid 904 flows radially into or out of a duct, users preferably configure and position a distributed contactor 260 across the opening of that fluid duct 130. The first fluid 901 is then desirably mixed with the second fluid 904 as it flows radially into or out of that duct. Users preferably size the orifices 80 such that when liquid drops are formed, they are entrained by the second fluid 904. In other embodiments, where some of the first liquid drops 901 settle out, users preferably provide a liquid collector 481 to recover that liquid 901 and recycle it.

14.11 Cross-Flow Evaporator

In other embodiments users configure a direct fluid contactor 483 in a cross-flow configuration with horizontal ducts. This is similar to the configuration shown in Figure 82.

Users preferably position an array of distributed contactors 260 across the horizontal duct 130 (instead of parallel to and above as shown). Users preferably position these contactors vertically across the entrance 134 to the fluid duct 130. A collection basin 481, pump 364 and return pipe is provided to recover droplets 901 that fall through the duct 130 before fully evaporating. Alternatively the distributed contactor arrays 260 may be placed horizontally across the upper portion of the duct 130 near the inlet 134 (as shown in Figure 82). In this case, orifices 80 are preferably sized to form drops that evaporate before reaching the bottom duct wall 132 to a desired probability by the time they reach the exit 136.

14.11.1 Layered cross-flow saturator

In other embodiments, users preferably enhance the evaporation and saturation uniformity by forming a multi-duct cross-flow evaporator 483. (See, for example, Figure 82.) They provide multiple generally horizontal duct walls 132 to divide the large horizontal duct enclosure 130 into multiple thin sub-ducts 131, thereby providing a more laminar fluid flow. They provide a distributed contactor array 260 across each thin horizontal duct 131. Users preferably position an array of distributed contactors 260 horizontally across the upper portion of each thin duct 131 near the inlet 134.

In this case, users size the orifices 80, length and height and number of thin ducts 130 to form numerous micro-jets and drops that do not completely evaporate by the time they reaching the bottom duct wall 132 near the exit 136. Users so size the number and size of orifices 80 and dimensions of the contactor array 260 and duct 130 to provide at least a prescribed mass flow rate, surface area formation rate and residence time of the first fluid 901 falling through the fluid duct 130 per mass flow of the second fluid 904 flowing through the fluid duct 130 for prescribed temperatures and composition of those fluids. By so doing, users can achieve a prescribed degree of saturation with a prescribed probability more efficiently and compactly than with the prior art. Users can similarly apply this methodology to the simpler cases of the other evaporator configurations.

14.12 Distributed Hydrocarbon Evaporator

Users preferably configure various evaporator embodiments 483 to evaporate hydrocarbon liquids including various petroleum distillate fractions, vegetable oils and liquid chemicals. These configurations are variously used to evaporate fuels 901 in oxygen

containing second fluids 904 such as in combustion systems, to evaporate chemicals in petroleum refining or chemical processing, to evaporate potable liquids in food processing, or to concentrate liquids in biochemical processing systems.

14.13 Delivering Fluids into Work Engines

In some embodiments, users use direct contactor arrays 260 or direct fluid contactors 483 to deliver one or more first fluids 901 into second fluid 904 to be used in work engines. For example, users preferably deliver one or more fuel fluids as the first fluid 901 into a second fluid 904 containing oxygen to form a mixed fluid comprising fuel and oxygen. (e.g., delivering fuel fluids such as natural gas or diesel fuel into oxygen containing fluids ranging from air to oxygen enriched air to oxygen).

14.13.1 Entraining through Cylindrical Wall Opening

In the relevant art, work engines are shown which draw their air in through openings, slots or perforations in or around a fluid duct 130, or in or around a fluid sub-duct 131 connected to such a fluid duct 130. E.g., a fluid delivery duct 131 connected to a cylinder, or within the cylinder itself. As shown in Figure 88, in some embodiments, users preferably place a cylindrical array 268 of streamlined perforated tubes 10 around the fluid duct wall 130 or 131 covering these openings. Users preferably wind streamlined perforated tubes around the fluid duct 130 or 131 over these openings in the direction circumferential to the relevant fluid wall 132. Users preferably connect both tube ends to a fluid supply manifold 240.

As shown in Figure 89, in other embodiments, users position the perforated tubes 10 of the cylindrical tube array 268 around the fluid duct wall 132 (cylinder wall) parallel to the axis of the fluid duct 130 or 131. Users preferably connect one or both ends of the perforated tubes 10 to a fluid supply manifold.

Where a reciprocating compressor or piston moves over such wall openings 196, users preferably provide cylinder slider wear bars 198 for the piston to ride on. The perforated tubes 10 are configured upstream of the slider wear bars 198 and preferably in line with them.

14.13.2 Delivering a Fluid through an Intake Duct or Port

As exhibited in Figure 90, in some embodiments, users position one or more

contactor arrays of perforated distribution tubes 10 across one or more intake ducts 131 to deliver at least one first fluid into the second fluid flowing through those ducts or ports into a larger cylindrical fluid duct 130. Such embodiments may use a planar array, conical array, or other contactor array as described herein.

In other configurations using arc or circular contactor tubes 10 about a cylindrical duct, users configure radial orifices 85 with multiple diameters to provide micro-jets with multiple penetration distances as desired. These are configured to penetrate a desired fraction of the radius from the peripheral fluid duct wall 132 towards the axis of the fluid duct 130.

They correspondingly configure the frequency and spacing of the orifices areas and micro-jet penetration distances to desirably fill the cross-sectional area to be covered at the respective jet penetration distances. For example, as shown in Figure 85, these long, medium and short micro-jets are preferably configured in the ratio of about 1:2:4 or similar ratios to spread the fluid over the duct cross section. E.g., user may select penetration distances of about 95%, 47% and 23% of the radius of the fluid duct 130 or sub-duct 131.

Users further configure combinations of contactor tubes 10 across the fluid duct 130, about or along the periphery of the duct 130 or 131, or about or along an axial hub of the fluid duct 130 in some embodiments.

As shown in Figure 86, in some configurations, users position one or more contactor tubes 10 around and/or along an axial fluid duct hub 137. They preferably configure the orifice diameters and spacing to desirably delivery micro-jets with multiple desired penetrations. The orifice spacing is correspondingly configured along and about the tubes to achieve the desired spatial delivery distributions of the first fluid 901 relative the second fluid 904 flow distribution to achieve desired spatial ratio profiles of those fluid distributions.

14.13.3 Delivering a Fluid into a Prechamber

With further reference to Figure 90, some work engines use prechambers 131connected to main cylinder(s) 130. In some embodiments, users position one or more perforated distribution tubes 10 around one or more ducts connecting to such prechambers 131 to deliver fluids into those prechambers 131. In another embodiment, the perforated distribution tubes 10 or contactor arrays 260 are positioned about or along ports 196 leading to or from such prechambers 131.

Where flow of the second fluid 904 through such sub-ducts or prechambers 131 into main chambers 130 is controlled by sub-duct valves 231, users preferably configure the contactor arrays 260 to desirably control the transverse evaporation time distributions and evaporation distance distributions relative to those sub-duct valves 231. These are desirably controlled to achieve desired degrees of fluid evaporation and mixing within the sub-ducts 131 and/or to control the level of splashing on the sub-duct valve 231 controlling that second fluid flow 904.

14.13.4 Delivering a Fluid into a Chamber

In some embodiments, with further reference to Figure 85, users preferably use a perforated distribution tube 10 around the periphery of the chamber or fluid duct 130. They preferably form numerous orifices 80 to inject numerous fine micro-jets of fuel into the chamber 130 at low pressure. The perforated tube 10 may be wound around the cylinder head space above the limit of piston travel. The orifices 80 preferably point towards the center of the chamber 130, away from the walls 132. More preferably providing some tangential orientation of the orifices 80 imparts some swirl component to the fluids and increases mixing.

This method permits the first fluid 901 (e.g., fuel) to penetrate and evaporate to a desired degree by the time the oxygen containing fluid 904 is compressed within the combustion chamber. This provides smaller more uniform drops with more uniform residence time. The results in significantly improved charge uniformity.

14.14 Delivery of other liquids

In some configurations, users use the direct contactor array deliver a fine spray of drops or "mist" of a lubricant into a transversely flowing fluid or gas. E.g., to add a suitable hydrocarbon, or hydro-fluorocarbon, water or other lubricant with desired transverse distributions of fluid flows to achieve the desired transverse distributions of composition or ratio of the first fluid to the second fluid. Some configurations deliver a fine mist of lubricants into refrigerants.

In a similar fashion users deliver cleaning fluids, refrigerants, fertilizers such as ammonia or other fluid with a desired transverse distribution of drop size and relative mass flows. In such configurations, achieving the desired transverse composition distributions are

often more important than any heat transfer involved.

15 POWDER FORMER

In further embodiments, users preferably form powders using one or more methods of liquid solidification, evaporation or chemical reaction.

15.2 Forming uniform liquid drops

The contactor 2 of Figure 1 and the other embodiments described herein may be used in some embodiments, to form fairly uniformly sized powders by delivering liquid drops through these distributed orifices 80 in the perforated tubes 10. Users utilize these distributed orifices 10 to form drops from molten liquid, from a reactive liquid, or from a solution or suspension. In such applications, users preferably place axial holes 84 at the downstream side of the perforated tubes 10, generally aligned with the axis of the fluid duct 130. They preferably control the differential ejection pressure across the orifices 80 to form fairly uniform pendant drops of the first fluid 901 to provide the greatest size uniformity.

Users preferably control the temperature of the liquid being delivered within a narrow prescribed range. This helps control the variation in surface energy, viscosity and density which affect drop size. Users preferably also control the temperature of the structure around the distributed orifices which helps control the solidification rate and solidification time.

15.2.1 Uniform micro-jets

In a similar fashion, users preferably form uniform micro-jets of fluid and adjust the differential ejection pressure to form drops with fairly narrow size distributions. E.g., by preferably maintaining the liquid jets in the laminar region and forming single micro-jets rather than sprays whose oscillations form fairly uniform drops.

15.3 Distributed Direct Contact Drier Spraying a fluid with slurried or dissolved materials into a hot gas is a common method of evaporating the carrier liquid, drying and recovering the solid materials such as milk powder. Users preferably deliver such compound fluids through embodiments of distributed perforated tube arrays to create drops with a desired transverse drop size distribution relative to a flow of second fluid flowing through the drier such as a heated gas. These drops are configured to evaporate within desired transverse distribution of residence times enabling much more controlled transverse distributions of evaporation distance. These measures of controlling drop size and

evaporation distance further reduce the frequency of very small drops and particles, thus increasing product recovery. The narrow drop and particle distribution further reduces or prevents the formation of large drops. This reduces residence time and liquid carrier liquid carryover into the product. Users preferably utilize the methods described with respect to Figures 18, Figure 19 and Figure 20 herein with adjustment for the evaporation rate caused solidification or powder formation within the drops.

As before, users preferably filter the compound fluid using a filter with a fairly uniform orifice size smaller than the product delivery orifices. With solids that tend to agglomerate, users preferably provide a wiper to remove solids built up on the filter. Users further provide a back flushing system to clear the filter.

15.4 Melt Drop Powder Former

In a similar fashion, users form powders from liquid melts, giving respectively more attention to radiation heat transfer than to evaporation. Users preferably hold the first fluid or "melt" temperature within a narrow prescribed range near the freezing point. With reference to Figure 91, they deliver the fluid through contactor tubes 10 with a large number of orifices 80.

As shown in the enlarged view Figure 92, the contactor tubes preferably have a combination of radial orifices 85, axial orifices 87 and intermediate angled orifices 86 to efficiently spread out the falling drops. The fluid flow through the orifices is preferably controlled to be in the laminar range to give more uniform drops.

With further reference to Figure 91, users preferably use a coolant flow through a coolant manifold 240 to maintain the duct walls 132 at a temperature lower than the temperature of the molten drops. Users further control the vertical length L (height) of the duct 130 (or "drop vessel") as a function of drop size to ensure sufficient residence time for the drops to cool and solidify. The thermal response time for drops to reach a prescribed fraction of temperature difference between the liquid melt and the walls is proportional to the drop surface area or the square of the drop diameter.

As before users preferably control the transverse distributions of contactor parameters of orifice size, position, orientation and fluid delivery pressure and temperature to achieve the desired transverse distributions of drop size and solidification distance. Users preferably use

orifices smaller than about 50 μm to obtain rapid cooling and small drop size. E.g., Reducing drop size from about 500 μm to about 50 μm achieves about 100 times faster equilibrium for the same mass. This method provides a significantly shorter drop height, faster production with associated benefits than the prior art.

15.4.1 Extended cool walls

With further reference to Figure 91, if the falling drops encompass a large cross section of the cooling vessel 130 as they fall, the interior portions will be optically hidden by other drops from the cool exterior walls 132 and not cool as fast as drops nearer the cool exterior walls. To improve cooling rates, users preferably provide additional intermediate vertical cooled walls 132 within the duct 130 to form fluid sub-ducts 131 to assist in radiatively cooling the falling droplets. For example, users preferably further intersperse perforated distribution tubes 10 with one or more cool duct walls 132 which can be cooled with duct wall coolant channels 138 carrying a cooled fluid. In other embodiments, these cooled walls may be formed from radiative finsfin-tubes 64. Users can use alternating drop passageways and cooled walls with perforated tubes above the passageways. These contactors 10 are preferably configured as rectangular arrays.

In some embodiments, users form the tubes, drop passageways and cooling walls in spiral or concentric forms. In other embodiments, users form cooling walls by using cooling vertical tubes carrying coolant interspersed across the drop space, preferably in a hexagonal pattern.

15.4.2 Drop through a vacuum

Molten metals often react with oxygen to form oxides. Many organic compounds similarly react with oxygen. To prevent or mitigate such reactions, users preferably evacuate the vessel through which the drops fall. The vacuum also eliminates convective cooling. The residence time for drops falling within the vessel is based on gravity caused acceleration. The dispersed cooling wall methods described above become even more advantageous with this configuration.

Users preferably use pipes for cooling surfaces as they can easily handle the pressure differences. In other embodiments, users can use coolant containing cooling walls where the walls are periodically bonded together to accommodate the pressure difference.

15.4.3 Drop through an inert gas

As a modification to falling liquid drops through a vacuum, users preferably deliver liquid drops to fall through an inert gas such as argon or possibly nitrogen. In calculating the drop velocity falling within the gas users preferably account for velocity dependent differential drag on the drop and buoyancy from differential density. In calculating the thermal residence time users preferably account for the influence of internal drop circulation on increasing heat transfer to the surface such as developed by Sirignano (1999) and others.

15.5 Uniform Powder Former by Reactive Liquids

15.5.2 Ultra Violet Solidification

Some chemicals are formed by exposing a reactive compound to Ultra Violet (UV) radiation. Users preferably form fine drops of the reactive compound with embodiments of direct contactor systems 2. Users then preferably send the drops through or exposed to an ultra violet radiation field. Users preferably form this UV radiation field with banks of UV lamps, preferably located at the foci of parabolic or similar reflectors to direct all the radiation across the falling drops. Users can also use vertical UV lamps with drops falling between them.

Often the UV radiation lamps are more intense and narrow. Consequently much of the UV radiation is poorly or non-uniformly intercepted by drops. Users preferably distribute the UV radiation more uniformly along the drop cavity. Users preferably provide reflective surfaces, linear Fresnel mirrors, or Fresnel lenses in a normal V or inverted V configuration in parallel with the UV lamps. In other embodiments, the UV lamps are interspersed among the perforated tubes, preferably above the drop space, but may also be below that drop space.

15.5.3 Drop through reactive gas

For liquids that react with a gas to form solids, users preferably form the drops with distributed perforated tube arrays 2. The reactive gas is flowed across the perforated tubes 10. The gas flow is preferably vertical to improve product uniformity. The drop residence time is preferably controlled to ensure a prescribed portion of the reactive liquid in the drops reacts with the surrounding gas.

16 RECOVERING DROPLETS & PARTICULATES

Direct contactor arrays may be used to assist in recovering droplets and particles in

some configurations. See, for example, Figure 87.

16.2 Gravity Settling In some embodiments, users configure a gravity separator in a very similar fashion to the direct contact heat exchanger 483 shown in Figure 82 to separate non-gaseous components from a fluid flow using gravity. E.g., to separate liquid drops and solid components from the flow. The gravity separator commonly comprises a generally horizontal fluid duct 130 that provides sufficient residence time for the non-gaseous components to settle to the lower side of the duct. To recover the first fluid, users provide suitable channels 481 to collect direct the first fluid flow to drains where they collect the fluid.

In some embodiments, users preferably select duct dimensions to provide a smooth laminar flow. Steps, baffles and other flow changes that cause eddies are preferably avoided. Users preferably utilize numerous fairly uniform orifices 80 to form fairly uniform micro-jets or fairly uniform drops of a first fluid 901 and deliver them to the fluid duct 130 to effectively contact the second fluid 904.

Where users form fairly uniform sized drops of the first fluid 901, this results in a generally uniform settling velocity across the second fluid flow 904. Fairly uniform drops have a fairly predictable residence time depending on where they are released, the relative uniformity of the flow, the difference in density, the viscosity of the second fluid, and the maximum duct height through which the drops settle. Users then select a length of fluid duct 130 long enough and/or the duct area large enough or reduce the velocity slow enough to provide the desired residence time so that they recover at least a prescribed portion of the drops.

16.3 Settling Planes As in the discussion herein on using multiple planes in layered cross-flow contactors and heat exchangers, users preferably provide multiple settling planes or duct walls 132 to form multiple sub-ducts 131 to recover the fluid 901 in some embodiments. (See, for example, Figure 82.) These settling planes 132 significantly reduce the distance droplets must typically travel before they contact one of these recovery planes 132. This correspondingly increases the separator effectiveness, reduces the duct length and reduces system costs.

Suitable methods are further described above in the discussion of the cross-flow

contactor, heat exchanger 483 and/or evaporator. As before, users preferably adjust the transverse distributions of direct contact parameters to achieve desired transverse distributions of settling time according to the respective second fluid parameters and duct parameters.

16.4 Cyclones

Cyclones are commonly used to recover drops and solid particles. However, conventional drop or particulate formation results in a wide distribution of drop or particulate sizes. The efficiency of cyclones drops off dramatically for smaller drop or particulate sizes. E.g., Kim and Lee (1990) measured the efficiency of a small cyclone 3.11 cm diameter by 9.5 cm high (barrel and cone). They found the efficiency drop off from 80% at about 7 microns to less than 10% at about 4.5 microns. Griffiths and Boysan (1996) obtained very close correlation with those experimental results by modeling the cyclone with Computational Fluid Dynamics using a Randomized Normal Grouping (RNG) based k-ϵ turbulence model to account for the swirling flow.

With a broad distribution, a cyclone will typically only recover a portion of the drops or powders. Often cyclones are sized much smaller and more numerous than needed for mean drops to recover smaller drops or particles. This undesirably requires many more cyclones. It also requires much higher pressure drops with higher pumping costs.

In some embodiments of distributed direct contactor arrays, users preferably generate fairly uniform sized drops or a narrow prescribed distribution of drop sizes. By using the analysis methods of Griffiths and Boysan (1996) users preferably obtain a cumulative distribution of drops recovered vs size. In modified embodiments, other suitable analysis methods may be efficaciously used, as needed or desired.

As shown schematically in Figure 87, the direct contactor array 260 is configured within the duct 130 to form the direct contact heat exchanger 483 shown here as an evaporative dryer. This is followed by a particle separator 520 shown here as a cyclonic separator. The first fluid 901 is delivered through the manifold 240 to the direct contactor array 260 through which it is sprayed into the duct 130. The second fluid is delivered to the direct contact heat exchanger 483 to flow through the duct 130 past the direct contactor array 260. In the evaporative dryer, the second fluid is preferably heated. The first fluid drops dry

to form particulates. Larger particulates are preferably recovered at the bottom of the direct contact heat exchanger 483. Smaller particulates are carried over into the particle separator 520 which collects a major fraction of the particulate carried out of the heat exchanger 483.

Using such methods, users preferably size the cyclone dimensions and flow parameters to achieve a prescribed cumulative distribution of drops recovered. By such methods, users preferably achieve greater than about 99% drop recovery at significantly lower rates of flow of the fluid per cyclone. This improves recovery and revenues and lowers pumping costs compared to conventional systems. In other embodiments, for the same gas flow rate, users can use larger or fewer cyclones and thus reduce operating and/or capital costs.

In modified embodiments, users use the experimental methods of Kim and Lee (1990) to obtain recovery efficiency versus drop size. Users then extrapolate the recovery efficiency versus size to identify the drop size at nominally 100% recovery. Users then select the drop size to be greater than the size needed to achieve greater than this nominal 100% recovery with the cyclone under consideration.

16.5 Electrostatic Precipitators Electrostatic precipitation technology is used to remove droplets or particulates from a gas stream. Prior art sprays result in a wide distribution of droplet or particulate sizes. Consequently, and disadvantageously, the electrostatic precipitation equipment are sized to remove the smallest particulates or droplets tolerable. Particulates smaller than that are undesirably lost with the exhaust gas flow.

16.5.1 Recovering liquid drops

In some embodiments, distributed direct contactors are used to form drops of the first fluid of fairly uniform size. This enables users to size the electrostatic precipitators and the voltages provided by the high voltage power supply used to remove these generally uniform drops. This provides a substantial reduction in size of the electrostatic precipitator and/or power required to recover a prescribed fraction of particles.

16.5.2 Recovering Solidified Powders

Users preferably utilize distributed direct contactors to form fairly uniform drops. Users solidify these drops to form fairly uniform powders. To recover these powders, an electrostatic precipitator is then provided. Users adjust the dimensions gas flow and power to

efficiently recover these fairly uniform particles. Users obtain greater recovery efficiency with associated benefits than the prior art.

16.5.3 Recovering Evaporated Powders

Users similarly apply this method with driers to recover the powders formed by drying fluids containing slurries or dissolved solids. By creating fairly uniform drops, users form much more uniformly sized powders. Users then recover these powders with this electrostatic precipitator method with greater efficiency and associated benefits than the prior art.

16.6 Impingement separators

Another common method of separating entrained droplets from the second fluid is to direct the flow through a tortuous passage which changes the fluid flow direction. A fluted array is commonly used to force the gas to change direction by traversing the flutes. Particles with a drop size and mass to drag ratio greater than certain values will impinge on the passage wall. Particles with smaller drop size and smaller mass to drag ratios will be carried on through by the gas.

By generating fairly uniform drops, users significantly improve recovery of impingement separators. Users preferably size the impingement passages, orifice size drop size and gas velocity such that most of the particles will impinge on the impingement separator with very few carried past the separator. Correspondingly users adjust the gas velocity and passage size to reduce the pressure drop and pumping cost of forcing the fluid through the impingement separator.

17 High Flux Solar Receiver

As with steam generation, heat recovery in concentrated solar collectors in prior art is typically limited by the material thermal stress limits. The solar flux is focused on tubes containing a fluid that is heated such as water or helium, or liquid sodium. In some embodiments, users preferably use distributed perforated tube arrays 260 to provide a dense "rain" of very small drops across the duct 130 receiving the high intensity concentrated solar flux, as shown in Figure 93. Users preferably use a suitable low vapor pressure metal or salt as the first fluid to form the drop arrays. E.g., gallium. Users preferably form the drops with a dense distributed array of perforated tubes 260 so that the drops form an optically thick

"fluid" to absorb the solar flux. The preferred configuration of the contactor tube 10 is shown in the enlarged view Figure 92. More broadly, the receiver is configured to have a view factor between 5% and 98% of that of a black body. The direct contactor receiver is configured to absorb 90% to at least 98% of the incident flux.

With reference to Figure 93, the receiver is preferably formed as a deep concave array to obtain the near "black body" (i.e., "gray body") high absorption benefits of a cavity. Users preferably focus the solar flux through portion of the duct wall 139 transparent to a desired range of electromagnetic radiation. E.g., using a sapphire window to form the transparent duct wall section 139 positioned to receive the solar flux. High purity sapphire windows can withstand the high solar fluxes and resultant high temperatures involved. In other configurations users use a clear quartz window. Users select the window thickness according to the vapor pressure of the fluid being heated. With a low pressure metal such as gallium, there is not a substantial pressure difference across the window so users can use a relatively thin window.

In other embodiments, users form the wall of the cavity with an array of sapphire contactor tubes. Users then pass the absorbing heat transfer fluid through the tubes and numerous surrounding micro-jets to absorb the heat from the solar flux. This helps cool the tubes as well as increase the optical absorption density within the duct 130.

18 GENERALIZATION

From the foregoing description, it will be appreciated that a novel approach for distributed contacting, mixing and/or reacting of two or more fluids has been disclosed using one or more methods described herein. While the components, techniques and aspects of the invention have been described with a certain degree of particularity, it is manifest that many changes may be made in the specific designs, constructions and methodology herein above described without departing from the spirit and scope of this disclosure. Where dimensions are given they are generally for illustrative purpose and are not prescriptive. Of course, as the skilled artisan will appreciate, other suitable nominal thicknesses, diameters, spacings and other dimensions and parameters for perforated tubes, tube arrays, and other components may be efficaciously utilized, as needed or desired, giving due consideration to the goals of achieving one or more of the benefits and advantages as taught or suggested herein.

Where tube or array configurations are provided, similar two or three dimensional configurations or combinations of those configurations may be efficaciously utilized. Where the terms fuel, diluent, water, air, oxygen, and oxidant have been used, the methods are generally applicable to other combinations of those fluids or to other combinations of other fluids. Where assembly methods are described, various alternative assembly methods may be efficaciously utilized to achieve configurations to achieve the benefits and advantages of one or more of the embodiments as taught or suggested herein.

Where transverse, axial, radial, circumferential or other directions are referred to, it will be appreciated that any general coordinate system using curvilinear coordinates may be utilized including Cartesian, cylindrical, spherical or other specialized system such as an annular system. Similarly when one or more transverse or axial distributions or profiles are referred to, it will be appreciated that the configurations and methods similarly apply to spatial control in one or more curvilinear directions as desired or prescribed. Similarly, the contactor, array, device or duct orientations may be generally rearranged to achieve other beneficial combinations of the features and methods described.

Where fluid delivery controls refer to controlling the size and flow rate of ejecting drops or micro-jets, it will be appreciated that the control measures may utilize one or more measures to control the differential ejection pressure distributions across the orifices 80, vibrate the orifices, and/or control the electric field outside the orifices 80 using one or more measures described herein or using similar means of modulating the orifices location, the fluid pressure and the surrounding electric field.

While the components, techniques and aspects of the invention have been described with a certain degree of particularity, it is manifest that many changes may be made in the specific designs, constructions and methodology herein above described without departing from the spirit and scope of this disclosure.

Various modifications and applications of the invention may occur to those who are skilled in the art, without departing from the true spirit or scope of the invention. It should be understood that the invention is not limited to the embodiments set forth herein for purposes of exemplification, but includes the full range of equivalency to which each element is entitled.